# Physiology of the Wildland Firefighter: Managing Extreme Energy Demands in Hostile, Smoky, Mountainous Environments

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## ABSTRACT

Wildland firefighters (WLFFs) are inserted as the front-line defense to minimize loss of natural resources, property, and human life when fires erupt in forested regions of the world. The WLFF occupation is physically demanding as exemplified by total daily energy expenditures that can exceed 25 MJ/day (6000 calories). WLFFs must also cope with complex physical and environmental situations (i.e., heat, altitude, smoke, compromised sleep, elevated stress) which challenge thermoregulatory responses, impair recovery, and increase short- and long-term injury/health risks while presenting logistical obstacles to nutrient and fluid replenishment. The occupation also imposes emotional strain on both the firefighter and their families. The long-term implications of wildfire management and suppression on the physical and mental health of WLFFs are significant, as the frequency and intensity of wildland fire outbreaks as well as the duration of the fire season is lengthening and expected to continue to expand over the next three decades. This article details the physical demands and emerging health concerns facing WLFFs, in addition to the challenges that the U.S. Forest Service and other international agencies must address to protect the health and performance of WLFFs and their ability to endure the strain of an increasingly dangerous work environment. © 2023 American Physiological Society. *Compr Physiol* 13:4587-4615, 2023.

## Didactic Synopsis

### Major teaching points

- Wildland firefighters (WLFFs) serve as the first line of defense to manage, control, and contain wildfires.
- WLFFs work within specialized teams and their operational tasks vary depending on the wildland fire management tactics employed for the active fire. Line crews take responsibility for constructing the fireline that contains the fire.
- WLFF must be physically fit to endure the long hours of physically demanding manual labor performed in a dynamic and complex environment.
  - The basic physical demands of the job necessitate a minimum threshold of pre-season physical fitness.
  - Line crew members in the United States must be able to pass a work capacity test called the Arduous Pack Test; which simulates the metabolic demands of the job tasks.
  - The metabolic demands of common fireline tasks have been and should continue to be used to drive policy and recommendations for pre- and early-season physical training and job qualifications.
- The physical demands of the WLFFs labor results in high daily energy expenditures and daily water losses.
  - Measurements of WLFFs on assignment using the gold standard doubly labeled water method reveal total daily energy expenditures ranging from 12 to 26 MJ/24 h (2800–6200 calories/24 h).
  - Nutritional support must overcome the logistical challenges associated with the remote locations of fire camps and a widely distributed workforce; some of whom may not be able to return to the fire camp between work shifts for several days.
  - Between-shift recovery of muscle bioenergetic stores can become compromised if adequate dietary carbohydrate is unavailable. WLFFs typically consume approximately 6 to 8 g/kg of dietary CHO each day

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when they are afforded sources *ad libitum*. When military rations (MREs) are provided, daily CHO intakes are considerably less due to the relatively low amount of carbohydrate in the ration.
  - Daily water losses and the resulting turnover which are largely determined by TDEE and the ambient temperatures in which the energy is expended typically range from 6 to 10 liters/24 h and 0.35 to 0.5 liters/MJ/24 h (1.5–2.0 liters/kcal/24 h). Fire management must ensure that sufficient fluid is available to meet these relatively large daily water losses.
- WLFF typically meet their daily energy, protein, and fluid needs.
  - Observational studies consistently reveal that body mass and total body water remain more or less stable day over day when adequate food and water is available.
  - Total daily protein intake usually meets or exceeds the recommendations for active individuals (approximating 1.8 g/kg/day).
  - Total sodium intake from dietary sources (solid foods and fluids) is generally >6000 mg/day, suggesting that additional supplemental electrolyte consumption is not warranted when adequate food is available.
- Tactical nutrition has shown potential for postponing fatigue and improving performance within a workshift.
  - Increasing the number of eating episodes that is, snacking, during the workshift, and the availability of supplemental-carbohydrate-rich sources have positively impacted workshift activity patterns.
  - Within-shift eating also appears to work even when WLFF consume insufficient energy to balance their daily energy expenditure.
- The physical and emotional demands of firefighting produce metabolic adaptations, but the magnitude and directionality appear dependent on the WLFF pre-season fitness and the environmental stressors they experience during the season.
  - Those who begin the season with higher aerobic capacity tend to detrain and those less fit during pre-season testing demonstrate positive adaptations across the season.
  - Within a crew, the alterations in sustainable metabolic loads become homogeneous and coincide with the upper metabolic demands of hiking on the fireline (~35 mL/kg/min).
  - Seasonal exposure to prolonged heat stress improves general heat tolerance in crews.
  - How muscular strength changes over the season is presently unknown.
  - There is evidence that metabolic health may be deteriorating across the season as negative changes in blood lipids, intrahepatic lipid, body mass, and body composition are being observed.
  - We speculate that the occupational stresses experienced during a season (i.e., perturbations in sleep, diet, smoke, stress, and various levels of fitness) interact synergistically to influence these postseason metabolic health status changes.

# Introduction

Wildland firefighters (WLFFs) are the first line of defense when fire outbreaks occur and are the critical human element for the emergency/management response to wildland fire. WLFFs are specifically trained to deal with fires burning on unimproved and mountainous lands. They are inserted at the fire outbreak and work to manage and suppress the fire. While much of their work entails manual labor, auxiliary heavy machinery, such as bulldozers, may be used to assist with the clearing of trees and brush to create large firebreaks to contain or steer the fire. Likewise, air support (specialized planes and helicopters) may lay down fire suppressants and water to dampen and slow the progression of a fire. The time a WLFF crew will spend at a given fire ranges from a few hours up to months-long engagements.

The hand crews carry their supplies and gear to and from the fireline daily, usually over undeveloped, rugged land. When at the fireline, they work with various hand tools (modified shovels, rakes, pick axes) to contain the fire; often on steep slopes and uneven terrain. Shifts are often 12 to 16 h long. The physical exertion of their labor and their time on shift can drive total daily energy expenditures (TDEE) up to 26 MJ/24 h (6200 calories/24 h) (40, 109).

Conflating to the exertional demands, the hand crews endure a myriad of occupational/environmental stressors including ambient and radiant heat (37), smoke exposure (83), nutritional challenges (39), acute and chronic fatigue/stress (physical, cognitive, emotional), and sleep disruption (5). These challenging environmental factors layered atop the arduous physical demands mean that physical injury risk is ever present.

In addition to the overt physical risks of the occupation, the emotional burden that WLFFs endure is just beginning to be understood from scientific and clinical perspectives. The unpredictable nature of wildfire can itself heighten anxiety. A separate and growing threat to the WLFFs emotional health is experienced through the repeated and extended time away from home. The problems presented by emotional separation are likely to worsen in years to come as wildland fires grow in intensity and frequency, necessitating an extension in length of the fire season.

The current collective understanding of the physical burden that WLFFs endure is based on detailed measurements acquired through a host of research approaches during active



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assignments (40, 96, 109), through studies in controlled laboratory settings (136), and from experiments in simulated field settings (137, 140). From these studies, we now have a good understanding of the necessary attributes to be a successful WLFF, the energy costs associated with WLFF manual tasks, the physiological strain they endure during wildland fire management and how WLFFs successfully self-regulate (15).

In this article, we describe how wildland fire crews are deployed and utilized during a wildfire outbreak. Moreover, this article details how the typical daily activities and environmental conditions alter the physical demands, in addition to the underlying physiological responses experienced by WLFFs on the fireline. Contemporary understanding for effective fatigue countermeasures (optimized early season training, workforce fitness requirements, and fluid and nutrient delivery) are discussed within the context of current best practices within the field. This article presents emergent evidence which demonstrates both potentially favorable (47, 71) and negative (29, 101) responses to the season-long stresses incurred by the WLFF workforce. In particular, the metabolic perturbations that may present over the course of a WLFF season will be discussed. Finally, this article summarizes both the acute (single or multiple work shifts) and chronic (seasonal) physiological responses in the WLFF so that clinicians, health care providers, trainers, nutritionists, crews, incident management teams, and administration can be better informed about this evolutionary topic.

# Wildland Fire Incidence and Management

Over the past 60 years, approximately 10% of the landmass in the United States has experienced a fire outbreak. These fires have erupted from natural causes (e.g., lightning) and human actions (either intentional or unintentional). In the western forested areas of the United States (US), the cumulative effects from generations of aggressive suppression efforts (19, 26) and prolonged drought have resulted in the accumulation of abundant dead/highly flammable material throughout the forest floor.

The historic fire of 1910, which famously impacted both Montana and Idaho, was a major precipitating factor behind the U.S. instituting a national policy of aggressive fire suppression. Portending of modern wildfire events, the landmark fire of 1910 was notable both for its intensity and the magnitude of land mass that was impacted. Over the course of 2 days, 3 million acres of land, timber, and structures were burned. A total of 86 persons died, most of whom were firefighters attempting to manage the fire. At that time, the country was well positioned for revolutionary change in governmental fire policy, as the U.S. Forest Service (USFS) had been created some 5 years prior to the 1910 blaze. Just as important, the WLFF workforce under the auspices of the USFS had matured to point where sweeping policy change directed at wildland fire suppression could be executed within a bureaucratic climate of relative efficiency (118).

More than 100 years later, it is evident that generations of aggressive fire suppression have led to the accumulation of flammable biomass over large swaths of land across the mountain west regions of the United States. Compounding the matter, drought conditions have emerged over the last 40 years as an independent factor, synergistically adding to the risk of hard-to-manage fire events. During this time frame, fire mitigation strategies have become more challenging too, as relatively dense suburban populations have encroached upon previously remote wilderness settings with significant fire risk (18). Given the ongoing warming of the climate, unprecedented wildfire frequency, and volume are expected to further threaten life and property (1, 126).

Today, fire management plans reflect the pragmatic understanding that wildland fire is a natural part of the ecological process. The tactical objectives outlined for managing wildfire incidents prioritize threats to life, private property, critical infrastructure, and cultural/national resources. The use of human resources (i.e., WLFFs) and combinations of heavy equipment (i.e., engines, bulldozers, and specialized aircraft) on wildland fire assignments vary dependent on the application of management strategies, containment options, and targeted suppression tactics. Within this dynamic context, WLFFs are frequently dispatched as the first line of defense, a fact that comes at the potential cost to both their acute and chronic health (13). The human element remains the cornerstone of comprehensive wildfire management.

# Wildland Fire Assignments

Wildland fire management teams organize specialized crews of WLFFs, in addition to ancillary resources to most effectively negotiate, manage, and/or actively suppress wildfires. Between fires, resource allocation depends on the incident location and the perceived risk to the various prioritized assets (life, property, environmental resources). While counterintuitive to some, rapid suppression may not always be the first priority when fires ignite in large forests on mostly uninhabited national lands devoid of critical resources. Instead, management teams implement strategies to identify the current and future fire behavior based on weather conditions and predictive models. In many instances, this approach may default to thrifty resource allocation (e.g., modest number of crews) if there is not an immediate need to establish a firm perimeter against well-established communities, neighborhoods, and other critical resources. Such circumstances are commonplace in large forests where built structures and communities are at relatively low risk based on the remote location of the fire, and regardless of the land mass involved. In contrast, when communities and structures (private homes, ranches, farms, and other economic or cultural settings) are threatened by wildfire, management teams more often shift their strategic priorities to containment and active



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suppression, attempting to minimize damage to the community, but maintaining firefighter and public safety as the first directive. Indeed, this approach becomes increasingly complex in areas identified as the wildland-urban interface, where moderately dense forest and expanded ground fuels mingle with community development and population expansion.

For large incidents of high priority, staffing of crews and management teams are organized around a central location or fire camp. Fire camps are mobile, temporary facilities that provide the infrastructure to accommodate sleep, food, and sanitation for the personnel deployed to the incident and serve as the central location of logistical and communication support for the large fire incident. Crews of WLFFs generally deploy from the main fire camp each morning after their daily safety and shift plan meetings and are typically transported to targeted drop points along the established operational perimeter of the fire. From there, WLFF crews ingress hike to the designated fire perimeter and as a team initiate fireline construction to limit the spread and/or deploy other tactics to best manage the fire's behavior.

## Wildland Firefighter Roles and Responsibilities

Wildfire assignments are typically in remote locations and accessible only by foot. The WLFFs traverse the difficult terrain packing the necessary gear, tools, food, and fluids to perform their daily shift work. The extensive physical demands of the job and the ground force operations they operate within have remained relatively unchanged from the early years of the USFS to the 21st century, regardless of the relative increase in wildfire activity and incident size. The physical demands of the job are persistent, ongoing, and require the deployment of an extensive and capable human workforce that is expected to sustain seasonal performance and health, despite repeated, daily exposure to environmental, and occupational hazards.

The USFS organizes the WLFF workforce by geographic region. Within any defined region, a range of different crew configurations are assembled and broken into districts, which may be associated with a specific National Forest, State, or county. Despite some organizational differences across the regions that affect the approaches used to manage and combat fire, there is consistency in regard to WLFF manpower organization. For example, there are two types of hand crews, designated as Type I and Type II. Districts commonly organize seasonal Type II hand crews (commonly consisting of 20 crewmembers) and these crews principally respond to and manage local wildland fires. If the National Preparedness escalates and requires that crew resources are needed to assist in other districts or regions, the Type II crew(s) may then be mobilized to support this need.

Type I hand crews are referred to as Interagency Hotshot Crews (IHC) and they are seasonally assembled to serve as a national resource and regularly leave their region and travel across the country, commensurate to the National Preparedness level and locations of wildland fire incidents of high priority. There are just over 100 IHC crews sponsored by the USFS, the National Park Service, the Bureau of Land Management, the Bureau of Indian Affairs, as well as state and county agencies.

IHCs are highly specialized hand crews. They possess demonstrated technical skills, have received extensive wildland firefighting training, and maintain advanced job-task qualifications (fire weather, fire management tactics, extensive wildfire experience). Commensurate with being given heightened responsibilities as compared to Type II crews, they also maintain a higher commitment to physical fitness standards. An IHC crew most often consists of 20 to 22 individuals and includes both females and males. Operationally, these crews are further subdivided into smaller modules/squads to perform the crew's wildfire management assignment most effectively. Squad members specialize in line construction or chain saw operation.

The combination of Type II and Type I IHC crews make up the majority of the workforce sent to high-priority incidents to physically combat a fire outbreak. Each crew moves between and within a fire location as a single unit. They travel in crew trucks of various sizes; such as dual cab $4 \times 4$ trucks and larger specialized crew carrier vehicles that can carry up to 8 to 10 crew members.

Hand crews rely on a few commonplace hand-held ground tools to control and suppress a fire. The most common hand tool is referred to as a Pulaski and contains a dual head including an axe blade to cut through small wood, branches, and roots and a flat adze (with a cutting-edge perpendicular to the handle) designed for scraping and shallow digging essential for hand crew fireline construction. Separately, trained teams of sawyers operate large chainsaws and take down trees, larger debris, and foliage that obstructs the fireline. Chainsaws' weights (~7–10.5 kg loaded with fuel and oil) and bulk (~70 cm bar length) require significant workloads to transport and operate using semi-static maneuvers. Sawyers carry the chainsaw, extra bar chains, oil, fuel, and other gear for their near-obsessive, maintenance of the saw. Sawyers also wear heavy Kevlar chaps to protect their legs from saw and debris hazards. Chaps are worn in addition to the standard personal protective equipment ensembles (high, mid-calf leather boots, Nomex pants, long-sleeve Nomex shirts, gloves, and hardhats). These details prove important to thermoregulation and daily energy expenditures, as crew clothing can weigh over 4.5 kg collectively, and hand tools (3.6 kg).

Collectively the teams of line diggers, sawyers, and swampers (tasked to remove foliage that accumulates on the constructed fireline once cut or dug up) work together in a unified effort to extend the construction of fireline along the designated perimeter of the wildfire. Their crew will operate in conjunction with other "like" crews, termed divisions, whom are likewise situationally positioned around the wildfire perimeter. The individual crew bosses maintain constant communication with their crews, with the other



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crews in their division, and the Incident Command Post. Designated crew members (crew or squad boss) also maintain communication to call in air support from specialized aircraft that deploy fire retardants and helicopters that can strategically drop large amounts of water onto hot spots or other designated locations (bucket drops).

Other specialized crews possess differing advanced skills and job-specific training. Helitack crews operate helicopters and shuttle WLFF teams to and from remote wildland fires. Their skill set provides rapid transport and a quick response capability to manage or assess wildfire outbreaks. Helicopter rappel crews rope rappel up to 75 m from the hovering helicopter to initiate suppression tactics in more isolated locations. Other air support-oriented crews include smokejumpers who are assembled near regional or local airports. Smokejumpers are dispatched to remote fire locations that are not commonly accessible by road. They are transported via aircraft (Short C-23 Sherpa) designed for parachute deployment and jump at moderate altitudes (1000 m). Smokejumpers use a static line parachute deployment system that results in an automatic opening upon exit from the aircraft. Once on the ground, smokejumpers assess the wildfire situation and develop a direct attack strategy. They are typically supplied to be self-sufficient for approximately 48 h of fire management.

A fire assignment is defined as the number of days between the first full operational period at an incident and the last day worked before returning to their home station or base. The standard assignment length for US crews is 14 days (extended assignments are possible), not including travel days to and from the incident location. Two days off are required following a 14-day assignment and return travel. While work shift length varies, incident management and crew bosses attempt to not exceed a 2:1 work shift to rest ratio to mitigate against fatigue and protect safety (i.e., 16-h work day: 8-h recovery at night). When shifts exceed 16 h of work, the corresponding ratio of rest must be accounted for in subsequent work shifts (4).

The season duration differs depending on job classification and crew type. Some crews see their employment status grow from 6 to 12 months, with job duties that include wildfire work and offseason fire management activities. Among IHCs, 1000 h of individual overtime is not uncommon during active summer fire seasons in the American West.

## Prehire Standards

All individuals seeking employment on a USFS hand crew must pass an aerobic performance test before they can be hired. The criterion performance task in use today is the USFS work capacity test (arduous pack test), an endurance walking test executed with a carried load. The performance standard is completion of 4.8 km (3 miles) over flat terrain in under 45 min while wearing a 20.4 kg (45 lb) pack or weighted vest. The pace required to achieve the standard elicits oxygen uptakes of 21.7 and 22.8 mL/kg/min for males and females, respectively (92), and closely aligns to the aerobic demands observed during simulated fireline experiments (114, 115). These average values for $\dot{V}O_2$ are also nearly identical to estimated values during average ingress-loaded hiking on wildfire assignments (120); giving the arduous pack test construct validity.

The evolution of the USFS prehire physical performance standard began in 1965 when it was determined that WLFF have an average oxygen uptake of 22.5 mL/kg/min when performing their fireline tasks (established from expired gas collections during simulated fireline construction). The rationale is based on the expectation that WLFFs can sustain occupational workloads of approximately 50% of their maximal aerobic capacity during extended operations. Therefore, based on the average energy cost of WLFF fireline activities (22.5 mL/kg/min), it was estimated that a WLFF would need to possess a maximal oxygen consumption of 45 mL/kg/min to successfully perform their work assignments for the duration of the fire season. Given this application of "*form follows function*," it is perhaps not surprising that a minimum threshold for aerobic capacity is still recognized by the USFS.

Initially, a step test or the 2424 m (1.5 mile) run was utilized as the criterion measure to rapidly estimate aerobic capacity of WLFFs (91). The step test required individuals to step on and off a 50.8 cm (20 inch) platform in a cycle of 2 s for 5 min. Both tests were abandoned in the late 1990s due to concerns that the tasks were not sufficiently job-related and that they did not adequately address components of muscular strength and endurance. This led to the development and adoption of the Arduous Pack Test, which remains in use today.

Smokejumpers have adopted more rigorous physical performance standards than the land-based hand crews. Their performance standards are maintained regardless of sex and are highlighted in Table 1, and compared to the scores other groups have currently or recently had for these same tests. The need for these additional performance tests is deemed necessary to ensure the individual has the necessary strength and stamina to perform the smokejumper's job-specific tasks and to operate unsupported for multiple days. Other hand crews do not have additional physical prehire standards outside of the arduous pack test.

## The Physical Demands of Working on the Fireline

Hand crews begin their workday with equipment prep, safety/shift briefings, and breakfast. Ambient temperatures during this portion of the day are cool to moderate. Afterward, the hand crews will typically drive to an accessible drop-off location near their assigned shift location and proceed the remaining distance on foot. Crew members carry all their required supplies, equipment, and gear for their work shift tasks. While the total distance traveled on foot varies considerably from day to day and fire to fire, in our observational studies, the ingress hike has been 20 to 60 min



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Table 1 Comparing Minimum Standards for Smokejumper and Military Physical Fitness Tests

| Test | Smokejumpers | Army APFT | Navy | Marines | Airforce |
|---|---|---|---|---|---|
| Pushups *(repetitions)* | 25 | Men: 42<br>Women: 19<br>*(2-min test)* | Men: 42<br>Women: 19<br>*(2-min test)* | Men: 42<br>Women: 19<br>*(2-min test)* | Men: 33<br>Women: 18<br>*(1-min test)* |
| Pullups *(repetitions)* | 7 | | | Men: 4<br>Women: 1 | |
| Sit up/crunches *(repetitions)* | 45 | Men: 53<br>Women: 53<br>*(2-min test)* | Men: 50<br>Women: 50<br>*(2-min test)* | Men: 70<br>Women: 50<br>*(2-min test)* | Men: 42<br>Women: 38<br>*(1-min test)* |
| Run pace *(min:sec)* | 4:35 min/km<br>*(2.4 km)* | Men: 4:58 min/km<br>Women: 5:54 min/km<br>*(3.2 km)* | Men: 5:18 min/km<br>Women: 6:15 min/km<br>*(2.4 km)* | Men: 5:45 min/km<br>Women: 6:25 min/km<br>*(4.8 km)* | Men: 5:40 min/km<br>Women: 6:49 min/km<br>*(2.4 km)* |

Values reported are for the minimal age group for each military branch. (Army = 17–21 years old; Navy = 17–19 years old; Marines = 17–20 years old; Air Force = ≤30 years old.) Smokejumpers do not have any differences in tests based on age or gender. Slight variations in test component techniques exist between each resource type.
For comparison purposes, fitness tests from the year 2018 are reported because of recent revisions to several military fitness tests.

in duration at an average speed of 3.4 km/h over terrain with an average grade of 4%. This ingress hike occurs during the early part of the day/work shift (usually between 07:30 and 11:00) when ambient temperatures are still lower, although air temperatures are rising and relative humidity has not yet decreased to respective afternoon values (120). In prior observational experiments, the average ambient temperature and humidity have been 21.9 ± 6.2 °C and 41 ± 15%, respectively (120, 121) but have fluctuated greatly across repeated days and incident locations.

While at the worksite, IHC crews work to create a fire containment line. This entails cutting and clearing trees, raking brush, and digging a continuous trench free of organic matter with the Pulaski tool. They work in tandem with aviation resources to create breaks between what will be burned and the land that they want to remain unburned. The energy demands of the specific tasks vary. Through a series of laboratory and simulated field experiments conducted by research teams in the United States and Australia, there is now consensus that the average energy cost for walking is approximately 6.6 kcal/min, chainsaw use is 5.0 kcal/min, with normal and urgent raking having average energy costs of 9.4 and 14.4 kcal/min, respectively (14).

Direct observation has proven useful for characterizing the WLFFs behaviors during their shift work and over the entirety of their day. In one study, activities characterized as light activity tasks accounted for 9% of the IHC crew member's time during their work shift, with moderate-intensity tasks accounting for 19% and high-intensity tasks for 28% of their total effort (132). The number of daily physical tasks WLFFs performed varied widely, with participants self-reporting 1 to 40 tasks per work shift. The average time on a specific task was 47 min. Tasks stratified in the light-intensity activity category include monitoring an existing fireline and working around a water pump or other mechanical equipment. Moderate-intensity activity tasks include activities such as managing smoldering debris with hand tools ("mop-up"), tree felling, and various light-digging activities and movement within or between assigned work areas on the fire. High-intensity activity tasks included hiking, digging handline (digging away organic materials and debris to reveal a continuous strip of bare mineral soil), and other related activities such as removing combustible fuels from a buffer zone around the assigned work area. Hiking consumed 19% of the total time they were engaged in high-intensity tasks. Moreover, nearly 20% of all IHC ingress hikes lasted longer than 30 min (120). The data also revealed that the time spent performing a specific task was longest when performing light-intensity tasks and shortest when performing tasks that aligned to the high-intensity activity category.

## Demographics of Type I and Type II Crews

Demographic examination of IHC and Type II crews indicated that they are approximately the same age (27 ± 6 years) and height (177 ± 10 cm), but the Type II crews possessed a higher body mass (Type II: 85.6 ± 14.0 kg vs. IHC: 81.6 ± 11.0 kg) and carry lighter equipment weight (Type II: 17.7 ± 3.2 kg vs. IHC: 20.0 ± 3.2 kg), suggesting some work capacity differences may exist between the crew types (120). Although there are differences between males and females for both height (males: 179 ± 9 cm vs. females: 167 ± 9 cm), mass (males: 86.0 ± 11.8 kg vs. females: 68.6 ± 8.4 kg), and body mass index (BMI) (male BMI: 27.0 ± 3.8 vs. female BMI: 24.8 ± 3.5), the two sexes carry the same equipment weight during the work shift (males: 18.7 ± 3.7 vs. females: 18.2 ± 3.6 kg). Accordingly, when equipment weight is expressed as a percentage of body mass, females are carrying a significantly higher overall load (males: 22% vs. females: 27%) relative to total body mass (120).



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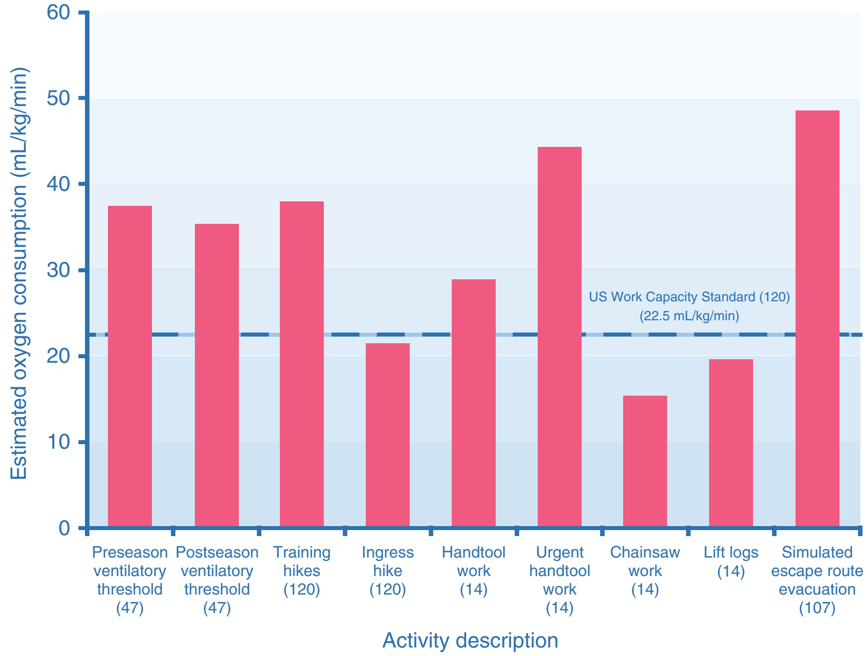


Figure 1 Expected metabolic load variability during wildfire management (simulated and live activities) and training/conditioning. Data collection during simulated fireline observation via indirect calorimetry (14). GPS derived estimated metabolic load during live fireline assignments and training (120). Measures of $T_{vent}$ prior to and following the season (47). Simulated escape from Ruby et al. (107).

There are relatively few peer-reviewed research papers characterizing the physical capabilities of WLFF. The available data indicate that their peak aerobic capacity values [$50.8 \pm 7.1$ (47), $53.2 \pm 5.2$ mL/kg/min (71)] are above population norms, and remain mostly stable over the fire season. Their preseason ventilatory threshold ($T_{vent}$) values ($37.5 \pm 7.0$ mL/kg/min) are similar to their preseason training hike intensities ($38 \pm 12$ mL/kg/min) and indicate the extent of preparation type I crews typically employ before the start of the fire season (47). Figure 1 depicts the measured and estimated oxygen consumption of WLFF-oriented fitness and job-oriented tasks relative to the required criterion work capacity test (arduous pack test).

The average strength characteristics of WLFFs have remained a relatively understudied topic. A recent foundational study did, however, examine the muscle strength characteristics of a combined group of active-duty urban firefighters and WLFFs (76 males, 4 females) (58). While the mean age of each subgroup from this study was older ($35 \pm 8$ years) than other WLFF studies referenced herein (109, 120), these data demonstrated that the majority of participants achieved a score of "excellent" or "good" on the YMCA bench press test ($44 \pm 17$ repetitions, males 36 kg, females 16 kg barbell, metronome at 60 beats/min). Similarly, most participants were categorized as above-average in the combined handgrip strength ($49 \pm 10.8$ kg) and Margaria-Kalamen stair climb test (72) for lower body power output ($1239 \pm 327$ W). It is important to note, however, that individuals in this mixed group of firefighters displayed lower peak aerobic fitness values ($n = 80$; cycle ergometer $= 38.4 \pm 6.8$ mL/kg/min) than have been observed by others (47, 71). While between-study discrepancies in peak aerobic fitness are not known, there is a rationale to suspect that differences simply reflect variability inherent to the testing modalities used between the two experiments. Nonetheless, it also remains possible that differences could represent some heterogeneity within the WLFF workforce, that is, district, rural, type II, and IHC cohorts.

Off-season training is necessary to meet the physical demands of the occupation. This requirement was illustrated by a cohort of Canadian WLFFs who exhibited below-average outcomes for the pushup ($27 \pm 9$ repetitions) and the combined grip strength ($78.5 \pm 21.0$ kg) portions of the Canadian WLFF fitness test (48). Yet, after this same cohort completed a 6 week training intervention to obtain a satisfactory score on the Canadian work capacity test (WFX-FIT test), the group achieved comparable peak aerobic fitness ($n = 71$; age $= 20.9 \pm 3.7$ years; graded exercise treadmill test $= 47.7 \pm 7.2$ mL/kg/min) scores as to those documented in the Gaskill et al. study (47).

## Physiological Responses During Wildland Fire Management

The introduction of portable wearable sensor systems has enabled relatively detailed characterization of WLFF work shift behavior. In some of our early evaluations, where



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measurements were captured over 3 days of an actual wildland fire assignment ($N = 15$, 3F, 12M, 45 total work days), it was observed that WLFFs spent $37 \pm 19\%$ of a respective work shift with a heart rate less than 100 bpm (40). When these data were stratified for intensity by heart rate, the relationship between heart rate and work duration was inversely related (i.e., 100–120 bpm = $25 \pm 12\%$ of shift; 120–140 = $20 \pm 8\%$; 140–160 = $12 \pm 8\%$; 160–180 = $4 \pm 5\%$; ≥180 bpm = $1 \pm 2\%$). Collectively, these data are interpreted to mean that WLFFs spend a relatively small percentage of their work shift engaged in high-intensity tasks and that objective physiological measures differ from direct observation and classification of job tasks previously used (132). These data also suggest that while work rates vary within the operational setting, WLFF self-regulate the intensity of their physical effort to adjust for the long duration of the work shifts.

Granular analyses of WLFF work patterns collected using wearable technology indicate that, in many instances, work profiles on the fireline vary as a function of the fire behavior and crew type. For instance, recent investigations indicate that Type I crews exhibited heart rates above 135 bpm for 20% to 75% of their shift, while Type II crews exhibited heart rates above this threshold for only 25% to 40% of their work shift. The specific tasks eliciting these sustained elevations in heart rate are common to both IHC and Type II crews and include ingress hikes, general shift work, egress, and within-shift team movements (120). It is important to note that these data were collected on a large, diverse sample ($N = 221$, 28F, 193M, 167 observational days across 50 wildfire incidents), giving weight to these collective observations as being more than anecdotal. From a physiologic perspective these novel insights derived from wearable monitors, in combination with well-established findings from prior research (100), suggest that a heart rate of 135 bpm approximates the ventilatory threshold of the average WLFF.

In addition to wearable devices, experimental grade thermistors, including ingestible temperature capsules, have been essential for understanding the physiologic stressors experienced while on duty. Studies employing ingestible temperature capsules reveal that WLFFs core temperatures ($T_c$) rise during shift work with the magnitude of hyperthermia commensurate with the energy cost of the shift work. The mean rise in $T_c$ during sustained (i.e., 47 min) light, moderate, and high-intensity activity WLFF tasks approximated 0.07, 0.18, and 0.38 °C, respectively (132). Importantly, observations from separate investigations suggest that the ambient temperature was only a modest contributor to the magnitude of $T_c$ observed, emphasizing the influence of metabolic work on heat accumulation (24, 121). The limited effect of ambient conditions on $T_c$ could be due to the effect of low humidity (and correspondingly low vapor pressure) on the promotion of heat loss through evaporative sweating. Moreover, it is highly plausible that WLFFs also self-adjusted their work pace in the hottest conditions, thereby masking ambient temperature-dependent effects on $T_c$, a trait previously suggested (15).

## Total Energy Demands of the WLFF

While global positioning system (GPS) tracking and work activity logs provide rough estimates of WLFF energy expenditures, the scientific assumptions inherent in the approach mean that the resulting data are approximations of the actual energy requirements. To overcome this knowledge between estimated and gold standard measures of energy expenditure, the first author engaged in a series of experiments in which the elimination of stable isotopes of hydrogen and oxygen (i.e., the doubly labeled water technique) was studied while WLFFs engaged in fire suppression across multiple assignments. The result of these efforts is a more complete characterization of the TDEE of WLFFs and the magnitude of variation between WLFFs and across fires (geographic location and terrain).

The TDEE is the sum of basal [basal metabolic rate (BMR)] or resting energy expenditure, the added energy expenditure associated with digestion of consumed foods and nutrients (dietary induced thermogenesis, DIT), and the energy cost of physical activity—often referred to as the energy expenditure of activity (EEA). In a well-controlled laboratory environment, these components are measured or approximated via prediction equations depending on the need for accuracy within the study design (50). In free-living conditions, however, less intrusive methods are essential to avoid interference with activity and natural workflow.

The doubly labeled water (DLW) method is a stable isotope technique that represents the gold standard approach to measuring TDEE in free-living humans (113). The DLW provides an unbiased derivation of overall energy metabolism without impeding an individual's activity or work schedule. Moreover, the DLW technique does not require cumbersome equipment and body-worn measurement devices (i.e., wearable biometrics or the collection of expired air samples).

Applications of the DLW method were initially used to characterize the variance in TDEE across different fire settings and geographic locations (40, 109). The participants in these early studies were members of two IHC crews and the variance in individual TDEE was captured as crew members worked on six fire assignments in six U.S. states (MT, CA, FL, WA, ID, CO). Importantly, the dosing and sample collection strategies were adjusted to accommodate researcher anticipation that WLFFs would exhibit high water turnover and to accommodate variability in participant shift schedules. Based on the early success with DLW in WLFFs, we subsequently used this technique to measure TDEE and water turnover in individuals engaged in unique ultra-endurance activities (38, 104, 106), remote expeditionary hunting in Alaska (27, 28), and military-oriented training exercises (36).

Briefly, the derivation of TDEE with DLW is determined by measuring the differential isotopic elimination of $^{18}O$ and $^{2}H$ (initially delivered orally in a water solution of $H_2{}^{18}O$ and $^{2}H_2O$ proportionate to estimated total body water) over multiple days. The basis of the isotopic technique enables the



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calculation of total body water, water turnover/flux (water in and water out), metabolic $CO_2$ production, and the average TDEE, MJ/24 h, kcal/24 h) over the sampling period (113). Although the DLW method does not have the resolution to obtain individual hourly or daily variations in energy expenditure, the data collected across the experimental period permit accurate approximation of the total water and energy requirements. In addition to the work mentioned previously, DLW has been used to quantify TDEE in a range of unique field settings including cycling (Tour de France) (135), high-volume swim training (124), military training operations (41, 59), mountaineering (Everest) (133), and spaceflight (64).

As stated previously, the initial experiments using DLW with WLFF crews took place on live-fire assignments and followed a selected group of IHC WLFFs as they engaged in a variety of wildfire assignments in multiple geographic regions (MT, CA, FL, WA, ID, and CO). Our initial goal was to quantify daily TDEE and the heterogeneity expected when working in areas with different terrain features, environmental temperatures, and assignment duties (109). Both females ($n = 9$) and males ($n = 8$) were recruited from local Montana IHCs. Despite differences in absolute TDEE (MJ/24 h) across the sexes, when expressed relative to overall body mass and estimated basal metabolic rate (xBMR), there were no differences between the male and female WLFFs (Table 2). Calculated TDEE ranged from 11.4 to 26.2 MJ/24 h; 2719 to 6260 calories/24 (1.8–3.6 xBMR). These values represent the average TDEE calculated from a 5 to 7 day measurement period during active wildland fire management work (un-simulated, nonprescribed burns).

We more recently used DLW to measure TDEE in a 15-year follow-up study conducted on IHCs ($N = 15$; $n = 12$ males, $n = 3$ females) battling a single wildfire in the Rocky Mountain region of Colorado (40) over three operational days on assignment. Implementing the identical isotopic approach and methodology mentioned above, TDEE ranged from 12.3 to 25.5 MJ/24 h; 2946 to 6083 calories/24 h (1.7–3.5 xBMR). TDEE was similar between sexes when expressed relative to body mass. Similar to our original study, body mass remained stable across the 72-h measurement period (77.3 ± 8.3 and 77.0 ± 8.9 kg pre and post, respectively) providing evidence that energy and water intake were sufficient to preserve body mass over the observation period. Table 2 provides a breakout of TDEE and EAA for females and males that participated in our initial study and this follow-up study. These two studies capture a total of 130 operational person-days of actual wildfire assignments and were gathered on $N = 17$ and $N = 15$ subjects, respectively (12F, 20M).

Other methods to estimate TDEE provide supportive evidence that the sample population in our DLW experiments are a representative cohort of WLFFs. In a follow on study to our DLW-based experiments, Heil (51) estimated the TDEE of WLFFs ($N = 10$) engaged in a 21-day deployment cycle using body-worn accelerometers. The estimated TDEE (kcal/24 h) was calculated from time spent sleeping and resting coupled with accelerometer output (counts/minute) across the range of light to vigorous activity. The author reported average TDEE values that were approximately 13% higher (19.7 MJ/24 h, 4716 ± 435 kcal/24 h) than in our DLW experiments. Yet, the corresponding values for EEA (10.1 ± 1.6 MJ/24 h, 2422 ± 375 kcal/24 h) were comparable to our two DLW studies (40, 109) (Table 2). We interpret the latter comparison to indicate that wearable biometrics can provide reasonable estimates of WLFF energy expenditure. When applied correctly, wearable biometrics may provide reasonable guidance so that nutrient requirements and recovery strategies can be adjusted appropriately.

## Energy Intake and Tactical Nutrition

One of the primary obstacles to supporting WLFF nutritional needs is getting food to the field kitchen. Base camps possess the necessary infrastructure to support the incident and are established in reasonably close approximation to the wildfire incident. Being proximal to the fire often means that the incident command postcamp itself is remote and dependent on continual re-supply as food and other consumable

Table 2 Total Daily Energy Expenditure (TDEE), Energy Expenditure of Physical Activity (EEA), and Changes in Body Mass (BM) During 3 to 5 Days of Wildland Fire Management Activities

| Sex | TDEE MJ/24 h, kcal/24 h | EEA MJ/24 h, kcal/24 h | TDEE (xBMR) | EEA (xBMR) | $BM_{pre}$, kg | $BM_{post}$, kg |
|---|---|---|---|---|---|---|
| F ($n = 12$) | 14.7 ± 2.6 (3514 ± 631) | 7.2 ± 2.3 (1726 ± 554) | 2.5 ± 0.4 | 1.2 ± 0.4 | 65.6 ± 7.1 | 65.4 ± 6.8 |
| Range | 11.4 to 20.6 (2719–4920) | 3.9 to 12.3 (936–2946) | 1.8 to 3.3 | 0.6 to 1.6 | | |
| M ($n = 20$) | 20.3 ± 3.2[a] (4853±764)[a] | 10.8 ± 2.9[a] (2589 ± 695)[a] | 2.7 ± 0.5 | 1.5 ± 0.4 | 77.8 ± 7.0[a] | 77.5 ± 7.7[a] |
| Range | 17.2 to 26.2 (2946–6260) | 3.8 to 16.4 (896–3904) | 1.7 to 3.6 | 1.0 to 2.2 | | |

Abbreviations: TDEE, total daily energy expenditure; EEA, energy expenditure of physical activity; BMR, basal metabolic rate; BM, nude body mass. Data are expressed as mean ± SD.
[a] $p < 0.05$ versus females. The average estimated EEA equates to carrying a 20.4 kg pack (45 lb) at a speed of 6.4 km/h (15 min/mile) for approximately 4.5 h (range = 1.7–7.5 h).
Values are compiled and combined from references Ruby et al. (109) and Cuddy et al. (40).



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items are depleted from the local inventory. The kitchens, themselves, consume raw food materials quickly. On a typical day, fire camp kitchens prepare two catered cafeteria-style meals (preshift breakfast and postshift dinner) and packaged lunches or shift provisions to sustain WLFFs during the work shift. Fire camp kitchens support both the ancillary base camp management members as well as the WLFFs directly. Depending on the size of the camp, a kitchen may be supporting hundreds to more than 1000 personnel daily.

A separate logistical obstacle is getting food to the WLFF. In certain fire situations, specific crews, to include smokejumpers and IHCs, are often not able to return to the base camp for food. Alternative strategies are often employed to supply fresh meals to crews that remain in locations that are remote to base camp. Hot meals, in some situations, are transported in warmer buckets and dropped off at prearranged coordinates. In other situations, alternative meal platforms, to include military rations, such as the meals, ready to eat (MREs) are used to sustain the WLFF. Air drop is a separate method to send food to their location. In some situations, food delivery is so challenging that individual crew units are required to subsist on their own stocked supplies and prepare them via campfire or camp stove individually or as crew/family-style meals. The USFS has become increasingly dependent on the MRE military rations during these situations.

To study the adequacy of the food support for meeting the WLFF energy needs, our research group and others have journaled the WLFF eating behaviors. These preliminary investigations of WLFF dietary practices were predicated on existing literature, indicating that humans can sustain a TDEE between 2.5- and 4.0-fold above BMR without compromising body energy stores (30, 123). Stability in the relationship between TDEE and the preservation of body energy stores is contingent upon the stipulation that sufficient foods are available to the research participants and that the meals are consumed to meet this added energy requirement. In our initial DLW study, we quantified work shift total energy intake (TEI) from individual food diaries and kitchen recipes. Across the days examined, TEI averaged $15.2 \pm 3.5$ MJ/24 h ($3632 \pm 837$ calories/24 h) (109), which was less than the average TDEE ($17.5 \pm 4.4$ MJ/24 h, $4183 \pm 1052$ calories/24 h) and amounted to an estimated deficit of approximately $\Delta 2.3$ MJ/24 h ($\Delta 550$ calories/24 h). Body mass was stable over the 5 to 7 day experimental sampling period ($69.6 \pm 8.6$ and $69.4 \pm 8.5$ kg pre and post, respectively). In the follow-up study (40) body mass also remained stable over the 72-h observation period ($77.3 \pm 8.3$ and $77.0 \pm 8.9$ kg pre and post, respectively). The stability of body mass over multiple investigations suggests that energy intake was sufficient to meet WLFF energy requirements and our estimates of TEI were likely to have been confounded by modest under reporting, a practice that is commonly observed with dietary recall and self-report food record inventories (46).

Extending upon this observation, we also found no apparent relationship between the maintenance of body mass and TDEE in the DLW data sets. While there were anecdotal examples of both positive and negative energy balance in the dataset, individual variance existed in both the lower and upper ranges of TDEE. This observation persisted whether the data were expressed in either absolute (MJ/24 h) or relative (xBMR) units of measure. When the data from all study participants ($N = 32$) were examined for measures of central tendency, the fold increase in EAA above BMR was nearly identical for the mean (+2.6), median (+2.6), and mode (+2.8). We interpret these findings in combination with the evidence of weight stability to indicate that the feeding practices employed by the kitchen crews provided a sufficient quantity of food for WLFF to meet their energy needs (total MJ or kcal) and there was ample time to consume dietary provisions.

Food diaries from these studies also reveal that the WLFF were eating a mixed macronutrient diet. When expressed as a percentage of the total intake, males consumed less CHO and more protein (PRO) and fat (CHO = $47 \pm 6$, Fat = $36 \pm 4$, and PRO = $16 \pm 3$%) compared to females (CHO = $59 \pm 8$, Fat = $28 \pm 8$, and PRO = $13 \pm 2$%). Daily CHO consumption averaged $6.5 \pm 1.7$ and $7.3 \pm 2.0$ g/kg BW/24 h for males and females, respectively. These values for daily CHO consumption are slightly lower than commonly recommended for endurance athletes (~10 g/kg BW/24 h) (16), but are similar to CHO intake of other populations' comparable levels of TDEE (41, 59, 124). In our initial DLW-based study (109) with WLFF crews on assignment, the nutrient intake records demonstrated an average daily protein intake of $2.2 \pm 0.6$ and $1.7 \pm 0.5$ g/kg BW/day for the men and women, respectively.

In a subsequent larger study ($N = 86$), WLFF TEI patterns were again quantified but this time using research assistants embedded within each WLFF crew cohort to tabulate nutrient intake more accurately and in greater detail (73). Each WLFFs work shift provision was preinventoried and loaded onto data collection tablets to catalog intake characteristics (intake timing and amount) throughout the single day. Although data was only collected throughout one continuous shift, these data provide a more detailed picture of self-selected eating patterns during live-fire operations. Results indicated that self-selected total daily energy intake averaged 15.4 MJ/day (3684 kcal/day). Total CHO and protein intake averaged 5.3 and 1.8 g/kg BW/24 h, respectively. These findings were extended by a subsequent study that included an expanded cohort of WLFFs ($N = 122$, 20F, 102M), and the same data logging methods were again used to examine eating behavior over a single day (12). Similar to the prior investigation, TEI averaged 16.3 MJ/day (3889 kcal/day). Total CHO intake averaged 5 and 7.2 g/kg BW/24 h, for males and females, respectively. Total protein intake averaged 2 and 1.9 g/kg BW/24 h, for males and females, respectively. However, due to crew travel logistics, participants were unavailable at the conclusion of the work shift, preventing measures of pre versus post-body mass.

Given the importance of normalizing macronutrient intakes to body mass, the aforementioned shadowing techniques were



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replicated during a different wildfire season in order the fully quantify the TEI patterns in WLFFs. The follow-up study included a sample of WLFF ($N = 71$, 10F, 61M) during a single live firework shift ($13.7 \pm 1.3$ h) (102). WLFF TEI averaged 16.7 MJ/day (3991 kcal/day). Total CHO and protein intake averaged 6.6 and 1.8 g/kg BW/24 h, respectively. During this data collection effort, measures of nude body mass were quantified in both pre and postwork shifts ($79.6 \pm 13.1$ vs. $79.3 \pm 12.8$ kg) demonstrating a minimal change in body mass ($-0.3 \pm 1.1\%$).

Taken together, these data suggest that WLFF have sufficient food available to replenish body energy stores depleted during a typical work shift. Data from these iterative investigations indicate that WLFFs make self-selecting dietary choices when provided with stocked fire camp kitchen options. However, these observations should not be interpreted to conclude that their diet and eating patterns are optimal for fueling work shift performance.

There are documented instances where daily carbohydrate and protein intakes have not met dietary recommendations, such as when subsisting on prepackaged military rations (77). Take, for example, a previous study that quantified the energy and macronutrient intake of WLFFs while they subsisted on either a single first strike ration (FSR) or two MRE over 2 days of live-fire assignment work (77). *A priori*, it was anticipated that the energy in these rations would not meet the WLFF's energy requirement (13.2 and 11.9 MJ/day for FSR and MRE, respectively). The impetus of the study was to determine whether the more eat-on-the-go capabilities of the FSR would increase *ad libitum* food intake when compared to the more meal-oriented MRE. Results indicated that the WLFF's indeed lost body mass (between −0.9 and −1.6 kg). In addition, their self-selected total CHO intake was 4.8 and 3.7 g/kg BW/24 h for FSR and MRE, respectively (77), a finding that was considerably less than the CHO intakes observed in prior samples of WLFFs that subsisted on field kitchen prepared meals. The average daily protein intake of 1.3 and 0.9 g/kg BW/24 h for FSR and MRE was also lower than what had been observed when subsisting on field kitchen meals. These findings indicate that while military rations may play an essential role in WLFF refeeding when field kitchens are unavailable, the lack of available energy and carbohydrate could become problematic if sustained for lengthy time periods on the operational fireline.

To address whether acutely limited CHO intake associated with MREs can become problematic for preserving muscle glycogen, muscle biopsy samples were collected from the quadriceps (vastus lateralis) in WLFFs before and after a live-fire work shift (39). Importantly, MRE provisions similar to Montain et al. (77) had been the WLFFs only source of subsistence for 1 to 2 complete work shifts prior to initiating the study. A striking finding from this investigation was that in more than half of the participants, the preshift glycogen levels were less than 80 mmol/kg tissue wet weight. We interpret this finding to indicate that the available CHO in this ration platform is not sufficient to restore muscle glycogen over several days of WLFF shiftwork. Moreover, the low initial muscle glycogen levels were coincident with lower-than-expected work shift activity counts, and more specifically activity counts commensurate with high-intensity work. This observation is important when compared to other cohorts with adequate total energy and CHO intakes needed to sustain energy and CHO balance on a daily basis. The persistence of suboptimal nutrition promotes a drop in preshift muscle glycogen levels, a finding that holds important implications for on-the-line work performances which may compromise WLFF safety.

## Opportunities for Tactical Nutrition

Given the volume of research conducted in athletic populations, many of the original nutritional recommendations for WLFFs were borne from sport applications. In this regard, a consistent recommendation within the endurance sport community is for periodic ingestion of CHO sources when athletes are engaged in prolonged sustained activity to improve work output and delay fatigue (31, 61). The consumption of higher percentage of CHO diets is preferred for endurance athletes that wish to optimize training and competition performance (10, 79). Thus, is it not surprising that similar dietary practices have been recommended for occupational athletes performing time-intensive and physically demanding work.

A consistent observation in the first author's early observational work was that WLFFs ate discrete meals separated by relatively long time periods of between-meal fasting. The two largest meals in terms of caloric intake were breakfast and supper, and these feedings were often separated by 12 or more hours depending on shift length. Moreover, the sack lunch provisions did not contain items that were easy to snack on during the work shift. These observations led to questioning whether this pattern of eating was ideal for sustaining WLFF work shift productivity and whether the National catering contract should be systematically re-evaluated.

Cuddy et al. (34) evaluated whether provision of frequent supplemental snack (high CHO and mixed macronutrient sources) feedings within a work shift would positively impact blood glucose and self-selected work intensities. Crews were provided a combination of liquid or liquid + solid high CHO options with the instructions to consume these supplemental products on an hourly basis. Subjects were provided supplemental food/drink materials at the onset of the work shift and directed to consume them on a regimented and timed schedule. Frequent radio communications between the research team and the crew members ensured dietary compliance throughout the shift. Consuming the CHO snack items at prescribed intervals during the work shift resulted in higher blood glucose values during the final 2-h of the shift compared to consuming the flavored, but CHO-free, placebo items (~6.5 vs. 5.0 mM). Despite neither group developing hypoglycemia, those consuming the CHO feedings, performed 20%, or 2.4 equivalent hours, more work, as measured by actigraphy, during a 12-h work shift as compared to placebo diet. During the placebo diet, WLFFs completed 47% less work in the last 2 h of the work shift compared to the CHO-supplemented work shift. The provision of the CHO snacks was not necessary either, as it was also determined that when WLFFs were encouraged to spread their lunch provisions throughout the work shift (at ~90-min intervals, enabling eight eating episodes on the fireline), work intensity remained stable. These consistent performances in WLFF-consuming partitioned lunches appeared to parallel the work outputs observed in the controlled feedings experiments (frequent consumption of liquid and liquid + solid CHO). These data suggest that the provision of higher CHO-containing food and drink options (25–40 g/h) and consuming them on the go while working, is a beneficial and practical approach to optimize work shift performance and may confer improved operational resilience and potentially safety. From these experiments and subsequent experimental studies (32, 45), there appears to be a wide variety of food options that could be used to support muscle CHO needs (commercially available sport-marketed liquids and food bars in combination with regular food items). This empirically driven conclusion is important in that it de-emphasizes the need for an exclusive supplement-oriented product.

The advantages conferred by frequent snacking during the work shift do not seem constrained to energy adequate diets. In the earlier described study examining the efficacy of the FSR versus the MRE during WLFF, actigraphy was used to examine activity counts within the work shift. Montain et al. (77) completed a repeated-measures cross-over design dietary intervention study whereby WLFFs subsisted for 2 days on a prototype version of the FSR, and for 2 days on MREs. Consistent with the hypothesis that snacking confers performance benefits, the authors found that when WLFFs subsisted on the FSR diet they not only had a larger TEI than when subsisting in MREs (FSR = 22.0 ± 2.4 and MRE = 18.4 ± 2.5 MJ/48 h, ~2600 and 2200 calories/24 h for FSR and MRE, respectively), they also accumulated more time performing higher intensity work, and spent less time engaged in lower intensity activities compared to when subsisting on the MRE provisions. This outcome from FSR consumption equated to the performance of approximately 24 additional minutes of high-intensity work and 30 fewer minutes of near-sedentary activity (based on accelerometer movement patterns). The results of this study provide additional supportive evidence that dietary strategies which facilitate more frequent eating during long hours of shiftwork are advantageous for sustaining performance as compared to the dietary constraints of discrete fasting periods separated by traditional meals.

The mechanisms of supplemental CHO consumption as a countermeasure to work fatigue appear to extend beyond muscle fuel levels. For example, during a single day, 10-h military simulation study that included a 19.3 km road march and two 4.8 km runs, the effectiveness of regular CHO feedings was evaluated (69). Subjects ($N = 143$) received either placebo, 27 g, or 55 g of liquid CHO at six feeding intervals over the 10-h study. Outcomes were evaluated by a plurality of performance measures that included metrics of reaction time, mental vigilance, and indices of cognitive readiness. The authors reported that both reaction time and mental vigilance were improved in the cohorts who received either CHO dose strategy compared to those consuming the placebo. The higher CHO feeding trial also improved physical performance (4.8 km run times), decreased metrics of confusion, and was associated with higher ratings of vigor (profile of moods states, POMS). These feeding doses from non-WLFF occupational studies largely support our observations in WLFFs (34). The potential benefits of regular CHO consumption during shift work are far-reaching, cost-effective, and can serve to better maintain physical and cognitive performance of WLFFs on the fireline.

The Standard Firefighting Orders include 10 best practices that are to be implemented during a response to wildland fires (4). Originally, established in the late 1950s, The Standard Firefighting Orders have been reviewed and refined over the subsequent decades. The provision of easily consumable eat-on-the-go CHO sources and the advantages they confer to WLFFs engaged in arduous labor directly align to three of the ten standard orders (6—Be alert. Keep calm. Think clearly. Act decisively; 8—Give clear instructions and ensure they are understood; and 10—Fight fire aggressively, having provided for safety first). Supplemental CHO enhances the ability to work more aggressively by increasing self-selected work rates (34) while also addressing cognitive metrics (reduced confusion, improved vigor) and maintaining alertness (69). During periods of more intense work, supplemental CHO may serve as an effective fatigue countermeasure that improves alertness and clarity of instruction while also enhancing overall fireline safety.

Based on the body of published research that has investigated supplemental feeding and dietary requirements for CHO, it is recommended that logistics personnel supporting IHCs adopt provision of multiple snackable high CHO food items in their lunch/takeaway meal kits (shift provisions) so that WLFFs have ready access to CHO sources and the ability to achieve (25–40 g/h of exogenous CHO) during their work shift. Adopting this strategy will provide the nutrient and energy to support segments of higher-intensity work, especially late in the work shift (34).

Attention should also be directed toward replacing depleted glycogen stores after higher-intensity work shifts by providing high CHO sources that are ancillary to the common kitchen meals or MREs. In circumstances where WLFFs finish a difficult work shift that has included repeat segments (15–60 min each) of high-intensity hiking, digging, other line construction or chain saw operation, periodic consumption of higher CHO food and drink options may be warranted to improve glycogen recovery prior to the next work shift. General guidelines suggest approximately 0.5 to 0.6 g/kg BW every 30 min (0.2–0.3 g/lb BW) (17). For an 80 kg WLFF, this recommendation would translate to approximately 40 to



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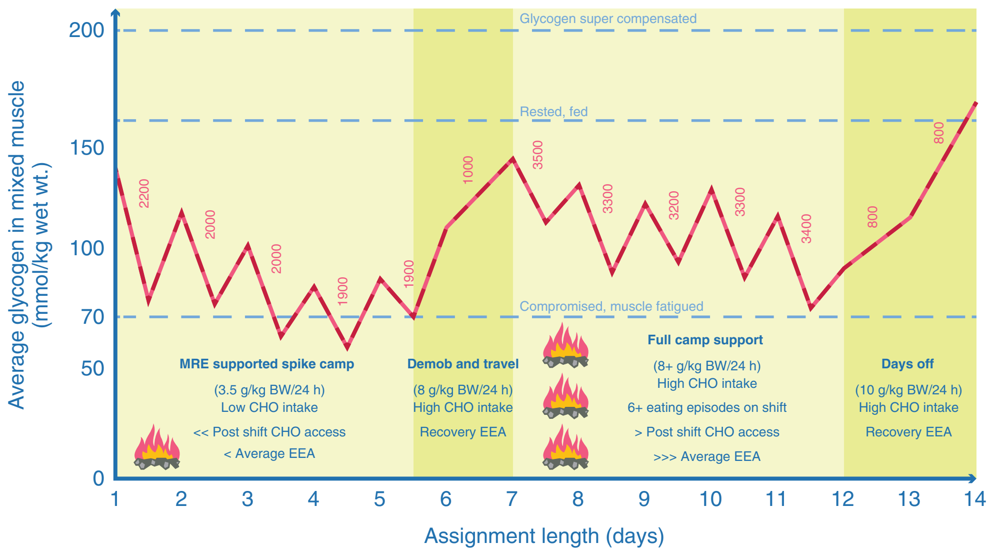


Figure 2 Theoretical model that depicts the implications of shift operations, the energy expenditure of physical activity (EEA), and nutrient intake on expected glycogen depletion and recovery (dotted line). Anticipated values of daily EEA are represented (800–3500 kcal/24 h) in red across the varied phases of an extended assignment. The campfire graphic represents the intensity of the wildfire assignment. Postshift CHO access is represented by lower levels of intake (<<) and higher levels of intake (>). The average expected energy expenditure of activity (EEA) is represented as less than average EED (<) or higher than the average EEA on assignments (>>>). The expected range of EEA values is derived from prior work (40, 109). The expected range of muscle glycogen values is derived from prior samples on the fireline (39).

50 g of CHO at regular intervals during the later afternoon and extending to the end of work shift, prior to dinner. While this aggressive approach may not be necessary after all work shifts, WLFFs should self-monitor subjective ratings of muscle fatigue to consider the degree to which diligent postshift CHO intake may be warranted.

Figure 2 depicts a theoretical example of work shift characteristics including the impact of work intensity (estimated EEA 800–3500 calories/24 h noted as vertical values in red for each day of the extended assignment), dietary support sources, total CHO intake, and access to CHO postshift. Based on the collective data (estimates of EEA) from our DLW studies (40, 109), supplemental feeding studies (34), and military ration evaluations (77), we postulate that when CHO access is low (MRE provisions only), even with lower levels of daily EEA, muscle glycogen may be progressively depleted over the first segment of an assignment. This conclusion is due to the observation that muscle glycogen restoration is incomplete between shifts, and importantly, may occur during instances of relatively lower EEA. During a theoretical second assignment in the above example, and despite scenarios of the higher-than-average EEA and elevated work intensity, the muscle glycogen lost during each work shift is more effectively restored due to strategic CHO intake (diligent intake during and postshift). On the 2 days off, when the EEA is reduced, muscle glycogen is further restored, and overall recovery is enhanced. We propose that when coupled with higher CHO intake, this 48-h recovery period results in improved glycogen levels thereby better establishing muscle readiness for the next assignment.

## Water Turnover and Fluid Intake

Daily water losses and the resulting turnover are dependent on TDEE and the ambient temperatures in which the energy is expended. As WLFFs perform long hours of physical labor and often sweat during their labor, it can be expected that they experience elevated daily water turnovers and water requirements compared to the general population.

WLFF's daily water turnover was first examined when this paper's first author deployed DLW to determine the TDEE of WLFF during actual fire suppression (109). He and others have subsequently used DLW (40) or a single, oral dose of deuterated water to determine water turnover at subsequent fires (40, 77, 108, 109). The results of these studies provide valuable insight for water planning and the factors that drive the measured water turnovers. Table 3 presents a synopsis of the experimental design and findings for these study groups.

In the first experiment (109), water turnover was quantified for WLFFs over a 5 to 7 day assignment in MT, CA, FL, WA, and ID in parallel with measures of TDEE. Each subject was studied at one of the five different locations for a 5 to 7-day wildfire assignment. Importantly, average nude body mass was unchanged (M = 74.6 ± 6.4 and 74.1 ± 7.2 and F = 65.2 ± 8.0 and 65.3 ± 7.6 kg pre- and post-experimental period, respectively). Across all five fires, the daily average water turnover was 7.0 ± 1.6 liter/24 h or 100 ± 20 mL/kg/24 h. This approach was repeated in our follow-up DLW study conducted on a single wildfire in CO, 15 years after the initial investigation (40). The measurement period included three work shifts and nude body



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Table 3 Changes in Body Mass Measures and Rates of Water Turnover from Deuterium Oxide ($^2H_2O$) Dilution During Live Wildfire Management

| Study | Wildfire suppression type | Preworkshift body mass, kg | Postworkshift body mass, kg | Body mass change, % | Water turnover, L/day |
|---|---|---|---|---|---|
| Cuddy et al. (40) | 3 consecutive days of 11 h of live wildfire suppression in the Western United States ($n = 15$) | 77.3 ± 8.3 | 77.0 ± 8.9 | −0.5 ± 1.5 | 9.5 ± 1.7 |
| Montain et al. (77) | 4 days of 11 h of live wildfire suppression during negative energy balance in the Northwestern United States ($n = 28$, 10 dosed with doubly labeled water) | Days 1 to 2: 70.0 ± 8.1<br>Days 3 to 4: 68.6 ± 8.1 | Days 1 to 2: 69.3 ± 8.1<br>Days 3 to 4: 68.1 ± 7.6 | Days 1 to 2: −1.9 ± 0.9<br>Days 3 to 4: −1.7 ± 1.3 | Days 1 to 2: 8.2 ± 2.2<br>Days 3 to 4: 6.2 ± 2.0 |
| Ruby et al. (109) | 5 consecutive days of ≥12 h of live wildfire suppression in the Northwestern and Southeastern United States ($n = 17$) | 69.6 ± 8.6 | 69.4 ± 8.5 | −0.2 ± 1.6 | 7.0 ± 1.7 |
| Ruby et al. (108) | 5 consecutive days of ≥12 h of live wildfire suppression in the Western United States ($n = 14$) | 71.9 ± 10.4 | 70.9 ± 10.2 | −1.4 | 6.7 ± 1.4 |

mass was preserved over the observation period (77.3 ± 8.3 and 77.0 ± 8.9 kg pre- and post-experimental period, respectively). Water turnover averaged 9.5 ± 1.7 liter/24 h or 123 ± 18 mL/kg/24 h.

*A priori* it was anticipated that WLFF with their relatively high TDEE coupled with working in protective clothing in warm conditions would have elevated water losses. But how do they compare to the general population and other athletic groups? Table 4 presents a detailed breakout of the WLFF data and like data drawn from the literature.

The data in Table 4 reveal that WLFF daily water turnovers are indeed higher than in less active individuals but are generally less than have been observed in athletes competing in ultra-endurance events. However, when the daily losses are expressed relative to energy expenditure, WLFFs have, on average, higher rates of water loss, and turnover than ultra-endurance athletes (0.46 ± 0.13 liter/MJ vs. 0.29–0.43 liter/MJ, for WLFF and Ironman, Western States 100, and the Race across America, respectively). We suspect that the latter is likely due to excess sweating due to their protective clothing and gear worn, the hotter ambient conditions on fire assignments, and/or a conscious attempt to ingest large amounts of fluids during the work shift to protect against dehydration and the accompanying added heat strain. Westerterp et al. (134) observed a similar inflation of water loss relative to energy requirement with a subgroup of females, but in their situation, attempting to manage cravings to snack. Therefore, it is reasonable to assume that some of the WLFFs may have been drinking more than their metabolic requirements to prevent dehydration.

The water turnover data also reveal that WLFF logisticians and crew chiefs should plan that crew members will consume water at 0.35 liter/MJ, (∼6 liter/24 h) and 0.50 liter/MJ (∼10 liter/24 h) when working moderate and higher itensity fires in warmer weather, respectively. And lastly, that adequate water appears available to the WLFF, as hand crews, as a group, are preserving their body water over repeated days of fire suppression duty.

The position stands from the American College of Sports Medicine (ACSM) (111) and the National Athletic Trainers Association (NATA) (74) recommend that athletes and individuals engaged in occupational labor drink sufficient water to prevent excessive dehydration, or a water deficit in excess of 2% to 3% of typical body mass, during physical activity. These organizational position stands and other authoritative sources (55) also encourage that excessive fluid intake be avoided, as exertional hyponatremia can compromise both performance and health. The current available evidence suggests that WLFF drinking *ad libitum* are drinking enough to protect against excessive dehydration and not drinking to excess.

In a study examining of WLFFs performing a variety of simulated wildland fire management activities, such as raking-oriented fireline construction and nonrake activities including sitting, standing, and walking) sweating rates ranging from 0.5 to 2.1 and 0.04 to 0.4 liter/h were reported for rake and nonrake activities, respectively (53). The sweat rates during the nonraking activities were positively correlated with body mass ($r = 0.72$) and ambient air temperature ($r = 0.93$). The work duration for this simulation averaged 5.4 ± 0.1 h and calculated mean hourly sweat rates were 544 ± 18 g/h. Measured fluid intake was 343 ± 14 mL/h resulting in a −1.5 ± 0.1% change in initial body mass.

Separately, we evaluated the fluid intake patterns during live-fire management work in the northwest part of the United States (Leavenworth, WA). Fluid intake and the pattern of drinking were quantified using a digital flow metered drinking reservoir system (35). During a 15-h work



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Table 4 Fluid Intake Relative to Measures of Total Daily Energy Expenditure of WLFF, Recreationally Active or Sedentary Adults, and Ultra-Endurance Athletes

| Location (reference) | BM, kg | TDEE (MJ/24 h), kcal/24 h | $rH_2O$ (liter/24 h), mL/kg/24 h | L·MJ/24 h | Weather activity | | RH, % | Season |
|---|---|---|---|---|---|---|---|---|
| | | | | | High, °C | Low, °C | | |
| MT (*n* = 1) (109) | 60.5 ± 0 - | 12.8 (3067) | 4.4 ± 0 (73 ± 0) | 0.34 ± 0 | 32.4 | 6.9 | 30 | Wildfire |
| CA (*n* = 4) (109) | 63.2 ± 10.3 | 18.7 ± 3.8 (4471 ± 906) | 6.5 ± 1.8 (102 ± 19) | 0.35 ± 0.1 | 38.9 | 23.4 | 25 | Wildfire |
| FL (*n* = 5) (109) | 71.1 ± 7.3 | 14.9 ± 2.2 (3554 ± 530) | 7.9 ± 1.0 (110 ± 7) | 0.53 ± 0.1 | 36.1 | 22.2 | 72 | Wildfire |
| WA (*n* = 4) (109) | 77.5 ± 7.3 | 16.5 ± 3.5 (3952 ± 841) | 6.4 ± 1.8 (82 ± 18) | 0.38 ± 0.04 | 32 | 17.7 | 28 | Wildfire |
| ID (*n* = 3) (109) | 68.4 ± 2.7 | 22.8 ± 3.0 (5450 ± 713) | 7.8 ± 1.6 (113 ± 19) | 0.34 ± 0.1 | 34.2 | 9.4 | 25 | Wildfire |
| CO (*n* = 15) (40) | 77.3 ± 8.3 | 19.1 ± 3.9 (4556 ± 943) | 9.5 ± 1.7 (123 ± 18) | 0.51 ± 0.1 | 34.0 | 20.0 | 25 | Wildfire |
| The Netherlands (134) | — | 11.6 ± 2.4 (2772 ± 574) | F, 3.3 ± 0.8<br>M, 3.6 ± 1.1 | F, 0.37 ± 0.1<br>F, 0.34 ± 0.1<br>M, 0.28 ± 0.03 | — | — | — | Summer |
| | | 11.5 ± 2.1 (2749 ± 502) | F, 3.1 ± 0.9<br>M, 3.4 ± 1.2 | F, 0.32 ± 0.1<br>F, 0.31 ± 0.1<br>M, 0.27 ± 0.1 | — | — | — | Winter |
| Ironman (*N* = 6) (38, 106)[a] | 70.4 ± 7.2 | 34.8 ± 6.3 10.8 ± 2.5 (8310 ± 1520) (152 ± 25) | 10.8 ± 2.5[a] (152 ± 25)[a] | (0.31)[a] | 33.0 | 21.0 | 70 | October |
| WS 100 (*N* = 10) (106)[a] | 71.4 ± 11.7 | 29.4 ± 5.7 8.7 ± 1.8 (7040 ± 1360) (123 ± 24) | 8.7 ± 1.8[a] (123 ± 24) | (0.29)[a] | — | — | — | June |

Abbreviations: TDEE, total daily energy expenditure; $rH_2O$, water turnover from $D_2O$ dilution (40, 109, 134).
[a]Values adjusted for 12-h measurement period (expressed as L·MJ/12 h).

shift, subjects consumed fluids exclusively from the provided reservoir system which was re-filled as necessary throughout the workday. Fluid was provided as either plain water or a water + electrolyte beverage (22.8 mmol/liter, 45 mg magnesium, 125 mg sodium, 130 mg chloride, 20 mg sulfate/liter) beverage. The total work shift fluid intake was significantly higher for the water only group (7.6 ± 2.4 liter) compared to the water + electrolyte group (4.3 ± 1.8 liter). Yet, only modest body mass loss was incurred across the work shift (78.1 ± 13.3 pre vs. 77.3 ± 13.3 post, −1% body mass loss) with no differences between groups. Because of the metered drinking system, drinking patterns could be quantified. Drinking volumes were highest during hours 6 to 13 (averaging roughly 0.8 liter/h), commensurate with the hotter portions of the day and the highest activity rates (accelerometer based). Drinking frequency was proportionate to increases in ambient temperature throughout the day and peaked at an average approximating 10 drinks/h.

Self-report fluid ingestion studies have also demonstrated important scientific insights. Raines et al. (96) asked WLFF to record their drinking over 2 days while on a wildfire assignment in Australia. The work shifts were 12.0 ± 2.6 and 11.8 ± 2.4 h with ambient temperatures of 30.9 ± 3.6 °C and 32.8 ± 5.7 °C on days one and two, respectively. Total fluid intake was not different between days 1 and 2 and averaged 6.4 ± 1.9 liter/day. Interestingly, approximately 20% of the postshift fluid intake was reported as beer (1.4 ± 0.8 liter), which is commonly restricted from established fire camps in the United States. Although pre- and postshift measures of nude body mass were not obtained, there were no significant changes in resultant plasma osmolality across either shift (pre vs. post and 2-h postshift); suggestive that their 24-h self-report fluid intake was sufficient to avoid excessive water deficits across the 2-day work window. Even when crew members were prescribed copious amounts of fluid during their work shift (1.2 liter/h), they chose to drink less



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(actual = 532 ± 232 and 218 ± 198 mL/h for the prescribed and *ad libitum* groups, respectively). Interestingly, there were no differences in hydration status, plasma sodium, or indicators of cardiovascular system stress between the groups (98).

The adequacy of work shift water consumption *ad libitum* has also been demonstrated in situations when common metrics of hydration status (urine color, specific gravity, and plasma osmolality) suggest that crews might have begun their work shift hypohydrated (97, 98). These and the aforementioned studies indicate that WLFFs with adequate work experience on the fireline typically self-regulate both work rates and fluid intake behaviors to protect against excessive dehydration. Table 5 provides a comprehensive review of fluid intake behaviors for crews on simulated and live-fire assignments (35, 37, 53, 65–67, 96–98, 108, 129) and on the impact of their behavior on overall hydration status. Collectively, the WLLF drinking behaviors appear to be preventing excessive dehydration and the associated deterioration in work performance and health.

Due to paucity of research on the optimal combinations of fluid volumes and intervals to enhance fluid retention and thermoregulation, it is reasonable to ask whether prescribed drinking might be advantageous over simply drinking to satisfy perceptions of thirst. In the early 1990s, Montain and Coyle (78) evaluated changes in esophageal temperature and serum sodium and osmolality during four different 140-min cycling trials in the heat (33 °C, 51% relative humidity (RH)) where fluids (1173 ± 44 mL of a 6% CHO, electrolyte beverage) were delivered after 0, 40, or 80 min of exercise. These single bolus trials were compared to a trial in which fluids were delivered at 0, 20 min, and every 15 min through 95 min of the 140-min trial. Due to fixed absolute drink volume, the intensity (70.5 ± 3.3% of $\dot{V}O_{2\,max}$), and the average sweat rates which approached 1.2 liter/h, subjects lost 2.9 ± 0.1% body mass. Although the more frequent fluid delivery attenuated the rise in body temperature and serum sodium and osmolality changes within the cycling bout, there were no between-trial differences at the end of the 140-min exercise period when participants had incurred the same magnitude of water deficit (78). These results suggest that drinking behavior can influence the physiological responses during exercise, but that the same physiological consequence will be incurred at a common level of total body water deficit.

In a related lab-based study, Rosales et al. (103) had subjects complete multiple trials with either a CHO, electrolyte mixture, or plain water. Fluids were provided commensurate to expected sweat rates as a single bolus (1005 ± 245 mL prior to each hour of a 2 h trial, 1.3 m/s, 5% grade, 33 °C, 30% RH) or as 22 doses/h (46 ± 11 mL/dose). Results indicated that there were no differences in body mass loss, urine production, heart rate, or skin and core temperature between the trials. These data revealed that at work rates in environmental conditions like those common to live-wildfire assignments, there is no apparent advantage to the way fluid was ingested. That is, despite sweat rates approaching 1 liter/h, heat management was unaffected when the isovolumetric bolus of water was consumed by gulps or sips. These data also suggest that fire crews may likely benefit most from frequent water breaks not because of regulated fluid intake intervals, but rather because of an interruption in metabolic heat production. Interpretation of this body of published work provides cumulative rationale for adherence to adequate work:rest intervals proportionate to the ambient conditions and to the metabolic demands. Additional protection is conferred by optimizing early-season aerobic fitness (33) and regular attention to fluid intake *ad libitum*. Historically, past research and wildfire agencies have over-emphasized the later without full consideration of the former.

## Is supplemental sodium warranted?

The general recommendations for sodium intake in sports beverages ranges from approximately 0.5 to 0.7 g/liter for events less than 3 h and 0.7 to 1 g/liter for events longer than 3 h. These recommendations are presumably based on the idea that very little if any mixed macronutrient dietary sources will be consumed during the event. These assumptions do not necessarily apply to WLFFs, as they have access to meals before, during, and after the shift. Therefore, consideration of the WLFF dietary sodium intake is necessary when considering if supplemental sources of sodium are merited.

Marks et al. (73) comprehensively quantified dietary intakes from camp breakfast and dinner, in addition to all provisions (liquid and solid) consumed during a 14.0 ± 1.0 h live-wildfire assignment. Sodium intake averaged 1685 ± 1353, 2417 ± 1174, and 2411 ± 1028 mg at breakfast, during the work shift provisions and dinner, respectively. Collectively, the average total 24-h sodium consumption exceeded 6500 mg.

Rosales et al. (102) provided additional insights for whether WLFFs may require supplemental dietary sodium while on assignment. In this investigation, the research team used data collection tablets on the fireline to quantify dietary intake, fluid consumption, and sodium intakes of WLFFs while they performed a single work shift (13.7 ± 1.3 h). The observed total daily sodium intake was 6628 ± 2186 mg, and body mass was unchanged across the work shift (79.6 ± 13.2 and 79.6 ± 13.1 kg for pre- and postshift, respectively). Total work shift fluid intake was 6.2 ± 2.3 liter and total work shift urine production was 2.5 ± 1.0 liter with a urine frequency of 5.7 ± 2.5 voids during the work shift. When work shift voids were compared (AM vs. PM), urine specific gravity remained stable (1.010 ± 0.007) throughout the day. Serum sodium was examined in a subset of the sample ($n$ = 25), and findings indicated that blood levels remained stable across the work shift (141.5 ± 2.4 and 140.8 ± 2.0 mmol/liter for pre- and postshift, respectively). The preservation of total body water coupled with the stability of postshift nude weight, urinary output, and serum hydration metrics collectively indicated that these WLFFs were in an approximate state of water balance at the end of their shift (preshift body mass ≈ postshift)



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Table 5 Measures of Fluid Intake, Changes in Body Mass, and Urinary Metrics on Baseline Hydration Status During Simulated and Live Wildfire Management

| Study | Wildfire suppression type | Fluid intake, mL/h | Fluid intake, liter/shift | Urinary metrics | Pre urinary metrics | Posturinary metrics |
|---|---|---|---|---|---|---|
| Cuddy et al. (35) | 15 h of live wildfire suppression ($n = 16$, eight consuming plain water, eight consuming electrolyte beverage) | Plain water: 504 ± 472<br>Electrolyte beverage: 285 ± 279 | Plain water: 7.6 ± 2.4<br>Electrolyte beverage: 4.3 ± 1.8 | USG | Plain water: 1.019 ± 0.007<br>Electrolyte beverage: 1.019 ± 0.005 | Plain water: 1.023 ± 0.010<br>Electrolyte beverage: 1.024 ± 0.009 |
| Cuddy and Ruby (37) | 7 h of live wildfire suppression leading to heat exhaustion ($n = 1$) | 840 | 5.9 over 7 h | — | — | — |
| Hendrie et al. (53) | 5.5 ± 1.4 h of live and simulated wildfire suppression (134 man-days of fire rake and nonfire rake, respectively) | Fire rake: 490 ± 262<br>Nonfire rake: 261 ± 139 | Fire rake: 0.92 ± 0.50<br>Nonfire rake: 0.90 ± 0.50 | — | — | — |
| Larsen et al. (66) | 3 consecutive days of 6 to 10 h of simulated wildfire suppression tasks ($n = 36$, 18 in 19 °C, 18 in 33 °C environments) | 19 °C: ~416 to 586<br>33 °C: ~451 to 1071 | 19 °C: ~3.5 to 4.6<br>33 °C: ~6.4 to 8.3 | USG | 19 °C: ~1.012 to 1.018<br>33 °C: 1.009 to 1.011 | 19 °C: ~1.010 to 1.011<br>33 °C: 1.006 to 1.009 |
| Larsen et al. (67) | 3 h of simulated wildfire suppression ($n = 10$, crossover in 18 and 45 °C) | 18 °C: ~430<br>45 °C: ~983 | 18 °C: 1.3 ± 0.5<br>45 °C: 3.0 ± 1.0 | USG | 18 °C: 1.014 ± 0.008<br>45 °C: 1.014 ± 0.008 | 18 °C: 1.016 ± 0.006<br>45 °C: 1.018 ± 0.007 |
| Larsen et al. (65) | 6 h of simulated wildfire suppression ($n = 38$, 18 in 19 °C, 20 in 32 °C) | 19 °C: ~300<br>32 °C: ~611 | 19 °C: ~1.8<br>32 °C: ~3.7 | Median interquartile range USG | 19 °C: ~1.019 ± 0.006<br>32 °C: 1.007 ± 0.007 | 19 °C: ~1.005 ± 0.003<br>32 °C: 1.003 ± 0.004 |
| Raines et al. (96) | 2 consecutive days of 12 h live wildfire suppression ($n = 12$, 10 of which recorded fluid intake) | 420 ± 132 | 6.4 ± 1.9 | Plasma osmolality | 292 ± 1 mOsm | 289 ± 0.5 mOsm |
| Raines et al. (98) | 10 h of live wildfire suppression ($n = 34$, 17 *ad libitum* consumption, 17 prescribed 1200 mL/h consumption) | *Ad libitum*: 218 ± 198<br>Prescribed: 532 ± 232 | *Ad libitum*: 3.4 ± 1.6<br>Prescribed: 7.1 ± 3.1 | Plasma osmolality, urine color (1 to 4, light to dark), USG | *Ad libitum*: ~295 mOsm, 2.8 ± 0.4, 1.019 ± 0.007<br>Prescribed: ~293 mOsm, 2.6 ± 0.5, 1.016 ± 0.005 | *Ad libitum*: ~288 mOsm, 2.3 ± 0.8, 1.016 ± 0.008<br>Prescribed: ~287 mOsm, 1.4 ± 0.5, 1.004 ± 0.002 |

(*continued overleaf*)



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Table 5 (*Continued*)

| Study | Wildfire suppression type | Fluid intake, mL/h | Fluid intake, liter/shift | Urinary metrics | Pre urinary metrics | Posturinary metrics |
|---|---|---|---|---|---|---|
| Raines et al. (97) | 10 h of live wildfire suppression ($n = 32$, 17 *ad libitum* consumption, 15 preshift 500 mL bolus consumption) | *Ad libitum*: ~340 | *Ad libitum*: 3.4 ± 1.6 | Plasma osmolality, urine color (1 to 4, light to dark), USG | *Ad libitum*: ~294 mOsm, 2.8 ± 0.4, 1.019 ± 0.007 | *Ad libitum*: ~288 mOsm, ~2.5, ~1.016 |
| | | Bolus: ~370 | Bolus: 3.7 ± 2.9 | | Prescribed: ~293 mOsm, 2.7 ± 0.6, 1.020 ± 0.006 | Prescribed: 286 ± 4 mOsm, ~2.4, ~1.015 |
| Rosales et al. (102) | 14 h of live wildfire suppression ($n = 71$, *ad libitum* fluid consumption) | ~443 ± 164 including food<br>~357 ± 150 without food | 6.2 ± 2.3 including food<br>5.0 ± 2.1 without food | USG | 1.010 ± 0.007 | 1.010 ± 0.007 |
| Ruby et al. (108) | 5 consecutive days of ≥12 h of live wildfire suppression ($n = 14$) | — | — | UOsmol, USG | UOsmol: 562 ± 175 mOsm<br>USG: 1.016 ± 0.006 | UOsmol: 629 ± 216 mOsm<br>USG: 1.018 ± 0.006 |
| Vincent et al. (129) | 3 consecutive days 6 to 10 h of simulated wildfire suppression ($n = 30$, 17 sleep restricted in 19 °C, 13 sleep restricted in 33 °C) | 19 °C: ~412 to 698<br>33 °C: ~722 to 1054 | 19 °C: ~4.2 to 4.8<br>33 °C: ~6.3 to 7.6 | USG | 19 °C: 1.015 ± 0.006<br>33 °C: 1.012 ± 0.008 | 19 °C: 1.011 ± 0.005<br>33 °C: 1.009 ± 0.007 |




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without supplemental sodium ingestion. It is noteworthy that no research subject in our studies with WLFF over the past 25 years has ever been treated for hyponatremia postshift.

Ultra-endurance triathletes offer a comparative model when considering if supplemental sodium is warranted in WLFFs. Athletes participating in full Ironman events perform sustained moderate-intensity work, incur large water turnover, and have race times comparable to a WLFF work shift. Because their energy expenditure is higher than WLFF, their sodium turnover provides insight into the upper-end need for WLFFs. Triathletes competing in the South Africa Ironman consumed *ad libitum* foods and fluids ($n = 61$) or an additional 156 mmol (3586 mg) of sodium ($n = 53$). The total sodium intake was estimated at 297 mmol (6828 mg) and 453 mmol (10,414 mg) for the control and experimental groups, respectively. There were no group-dependent changes in serum sodium levels in pre- versus postrace measurements (control = $140.7 \pm 1.7$ and $140.5 \pm 3.5$ mmol/liter pre and postrace; experimental = $140.6 \pm 1.7$ and $141.5 \pm 2.7$ mmol/liter pre and postrace, respectively) (56). The authors concluded that supplemental sodium consumption above *ad libitum* levels was not required to maintain serum sodium concentrations.

In a similar study at the Ironman World Championships in Kona, HI (87), subjects demonstrated a $1.45 \pm 1.6$ kg body mass loss and a change in serum sodium ($145.4 \pm 2.1$ and $142.8 \pm 4.4$ mmol/liter pre- and postrace, respectively). Nutrient intake was monitored on a subset of the subjects ($n = 20$). Fluid intake averaged $12.4 \pm 4.0$ liter and total race sodium intake was $257 \pm 122$ mmol ($5980 \pm 2804$ mg). The combined data from Ironman events and data collected on the fireline indicate that supplemental sodium either during or after the work shift is unnecessary if WLFFs have access to the camp-prepared foods and are allowed to eat *ad libitum*. It is still unclear whether dietary sodium intake is adequate when WLFFs subsist on military rations during operational assignments resulting in negative energy balance.

# Physiological Adaptations Across the Fire Season

Off-season training is a compulsory activity to prepare for the physical demands of the fire season and the long duty shifts (47). Early studies of the population indicated that WLFFs utilize hiking, with and without load carriage, as one of their primary pre/early-season training modalities (42, 114, 115). Hiking in itself provides significant health benefits without prerequisite skills and/or equipment demands (76). Even with the availability of a host of modern-day training tools, hiking remains one of the most pragmatic and cost-effective training modalities available to improve overall work-specific fitness in WLFFs (25). Hiking also provides a highly task-specific overload stimulus for the work capacity test that was developed to assess adequate preseason preparation (114).

The oxygen consumption estimates during the preseason training hikes ($38 \pm 12$ mL/kg/min) have been observed to be consistently higher in IHCs than their Type II counterparts (120). This conclusion is evidenced by the fact that IHCs walk at a faster speed ($\Delta = 0.2$ m/s) for longer durations ($\Delta = 19$ min) while carrying a load similar to what they will carry during the season. The higher estimated steady-state $\dot{V}O_2$ of the IHC training hikes are in the upper 17% of performances observed during ingress hikes on assignments.

One might assume that the arduous nature of seasonal wildland firefighting would result in continued and consistent improvements in physical fitness in WLFFs. Group-wide improvements in fitness, however, are typically not observed, or are modest in magnitude when they occur. The studies to date indicate that as a group, aerobic fitness has remained similar to baseline (47) or was only modestly improved (+3%) after a fire season (71). Gaskill et al. (47) reported that $T_{vent}$ values decreased from $37.5 \pm 7.0$ to $35.4 \pm 2.3$ mL/kg/min over the course of a season when they followed four independent crews ($N = 65$). The lack of group change is, however, masking the within-group pattern. When individual WLFFs in these datasets are stratified according to their baseline (preseason) $\dot{V}O_2$ peak, those that were less aerobically fit before the season became more fit, whereas those with higher initial $\dot{V}O_2$ peak values incurred a loss in aerobic fitness over the season. The same pattern emerges in their pre- to postseason sustainable aerobic capacity ($T_{vent}$) scores. These data suggest that WLFFs are adapting to the physiological requirements of their labor (47); for some this requires a training effect, whereas for others, a modest detraining adjustment.

It is well described that significant reductions in aerobic conditioning will occur within as few as 2 weeks when the training stimulus is discontinued (85). WLFFs that begin the fire season aerobically fit will, therefore, require inclusion of greater intensity exercise than the WLFF tasks require if they desire to maintain their preseason fitness levels throughout a season of firefighting (70).

To date, changes in muscle strength and work task stamina have received limited attention. Also unclear is how measures of upper and lower body strength change across a season compared to measures of aerobic power and/or sustainable fitness ($T_{vent}$). Considering injury risk related to slips, trips, and falls, additional information regarding the strength demands of wildland fire management is warranted and represents a necessary research direction.

## In-season WLFF physical activity and the blood lipid paradox

A physically active lifestyle is recommended to improve blood lipids and other health status indicators (9). Given the physical nature of wildland fire management, it might be expected that blood lipids and health status markers would



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be low and maybe improve over a fire season. Yet, such favorable adaptations to WLFFs have not been observed to date. Instead, when examined, a pattern in the direction of poorer lipid status is emerging and presents a *pathogenic paradox* that is an active area of new investigation.

We first had the opportunity to examine how a variety of health status markers adapted to the seasonal stress of wildland fire management in a cohort of Alaska-based WLFFs ($N = 27$) who were deployed a total of 63 operational days between the months of June and September (29). We found that over the observation period, several changes were apparent via dual-energy X-ray absorptiometry scans, magnetic resonance imaging/spectroscopy scans, and blood work. Total and visceral fat mass were increased across the season (total = 12.4 ± 5.2 and 13.9 ± 4.9 kg, visceral = 318 ± 47 and 419 ± 48 g for pre and postseason, respectively). Total cholesterol and low-density lipoprotein (LDL) were also increased (total cholesterol = 162 ± 28 and 180 ± 34 mg/dL, LDL = 86 ± 23 and 100 ± 32 mg/dL for pre and postseason, respectively). Although not statistically significant, intrahepatic lipid demonstrated an increased trend from baseline (+30%, $p = 0.06$). These seasonal perturbations in atherogenic blood lipids have now been corroborated in a larger sample of WLFFs ($N = 100$, 92M, 8F) from Montana and California crews (in response to >100 operational days deployed) (101). Similar to our study in Alaska, total cholesterol, LDL, VLDL and triglycerides were increased across the season (total cholesterol = 173 ± 31 and 178 ± 28 mg/dL, LDL = 93 ± 28 and 97 ± 25 mg/dL, VLDL = 14 ± 7 and 18 ± 10 mg/dL, triglycerides = 71 ± 33 and 90 ± 51 mg/dL pre and postseason, respectively). In contrast, HDL was numerically reduced (66 ± 16 and 64 ± 13 mg/dL, pre and postseason, respectively). While these values remain in the normal range, we have identified negative direction changes now in two different cohorts. Whether these changes are potentially heightening the seasonal risk of developing insulin resistance and metabolic diseases during wildland fire operations remains unknown (110).

We suspect that several factors may be overriding the beneficial influence of human movement on these health status indicators. These factors include, but are not necessarily limited to: (i) smoke exposure/inhalation, (ii) deconditioning, (iii) stress, (iv) sleep, and (v) dietary intake (47, 82, 117, 130). Table 6 outlines some of the measured changes, both positive and negative, for multiple health status indices that have been examined over a wildland fire season.

## Occupational Hazards and Other Health Concerns

### Heat stress

The ambient temperatures on wildland fire assignments are generally warm to hot. In the datasets we have collected, the ambient temperatures in the highest quartile have ranged from 29.0 to 49.1 °C, whereas the lower quartile has spanned from 13.3 to 25.1 °C. Although some of the ambient weather conditions have exposed the WLFF to moderate- to very high risk for experiencing heat illness (24), the observed mean $T_c$ and skin temperature ($T_{sk}$) values indicate that the crews appropriately modified their work intensity and/or added longer rest periods in these conditions to avoid heat strain (40). Likewise, activity counts (via actigraphy) amongst teams studied and operating in mild to warm ambient temperatures have been similar, whereas there has been a modest reduction within teams operating in the hottest temperatures (13.3–25.1 °C = 540 ± 637 counts/min; 25.2–26.4 °C = 538 ± 665 counts/min; 26.5–28.9 °C = 570 ± 638 counts/min; 29.0–49.1 °C = 487 ± 449 counts/min) (121). This observation of relatively consistent activity rates across the ambient temperature ranges suggests that the pace of their work can be preserved over a fairly wide range of ambient temperatures and is appropriately modified in more extreme ambient temperatures.

The clothing and equipment worn by the WLFF impede heat transfer to the environment. All WLFFs wear a fire flame-resistant long sleeve work shirt and pants consisting of Nomex® material along with protective heavy leather boots that extend above the ankle and a hard hat and leather gloves. Prior studies on these ensembles have established that there is an increased thermal demand associated with activity when wearing these protective garments (49, 112). Moreover, these uniforms will induce an upward shift in the thermal strain-metabolic rate and ambient temperature relationship and likely lower the critical ambient temperature where work:rest schedules need to be adjusted to avoid excessive thermal strain and heat illness.

To gather data on the magnitude of hyperthermia being experienced on the fireline, West et al. (132) measured the body core temperature responses of 298 WLFFs while they performed their live-wildfire assignments. They observed that the WLFF $T_c$ during their shift work was proportionate to the work intensity and the duration of each intermittent activity segment within the work shift. A Δ + 0.5 °C rise above baseline was observed when higher work intensities were maintained for approximately 75 min. The peak $T_c$ observed was approximately +1.5 °C above baseline when WLFFs were engaged in higher work intensities work and this level of effort was sustained greater than 300 min. Importantly, job task (intensity of work) and duration were identified as modifiable risk factors to reduce the $T_c$ rise and heat injury risk. To date, this study is the most comprehensive characterization of the thermal strain being experienced by WLFFs on live-fire assignments.

Established heat illness prevention guidelines within wildfire agencies often emphasize drinking as a key practice to avoid heat injury. Drinking mitigates the accumulation of excessive dehydration but by itself is not protective against heat injury. Rather, the best protective measure is to reduce exercise intensity and the insertion of rest breaks to lower the thermoregulatory burden imposed on the individual. An



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Table 6 Documented seasonal changes in wildland firefighters

| Study | Body mass | LTM | FM | Visceral fat | Total cholesterol | LDL-cholesterol | VLDL-cholesterol | Intrahepatic lipid | Aerobic fitness | Blood pressure | Grip strength |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coker et al. ($n = 27$) (120) | ↑ | ↔ | ↑ | ↑ | ↑ | ↑ | ↔ | ⤴ | ø | ø | ø |
| Dodds et al. ($n = 100$) (91) | ↑ | ø | ø | ø | ↑ | ↑ | ↑ | ø | ↑ | ↓ | ↔ |
| Gaskill et al. ($n = 65$) (114) | ↓ | ↓ | ↓ | ø | ø | ø | ø | ø | ↔ | ø | ø |
| Lui et al. ($n = 12$) (115) | ↔ | ↔ | ↔ | ø | ø | ø | ø | ø | ↑ | ø | ø |

Abbreviations: LTM, lean tissue mass; FM, fat mass.
Large arrows indicate significant alterations ($p < 0.05$), whereas ⤴ indicates a strong trend ($p = 0.06$). Horizontal arrows indicate no significant alterations ($p > 0.05$). "**ø**" Indicates variable not measured.

exemplar of this point comes from a subject participating in the metered fluid intake study cited in the fluid intake section (35). In this instance, the subject developed a heat injury requiring medical intervention 7 h into one of the work shifts (~1430 h). Because monitoring instrumentation was integrated as part of the investigation, we were able to capture this WLFF's physiology as the heat-related injury (HRI) evolved (37) and can compare this individual's data to the physiological responses to fellow crewmates (35), in addition to other core temperature response data (121) in our database. The affected individual's data are illustrated in Figure 3. In the 7 h leading up to the HRI, this WLFFs work rate (measured by actigraphy as above) was the single highest individual work rate captured within the scope of our decades-long research in this area. Specifically, this body of work encompasses 132 subjects observed over a duration of 321 work days (34, 35, 77). In the 2.5 h leading up to the HRI, the affected individual was exposed to 113 min at ambient temperatures ≥40 °C, of which 41 min were at air temperatures ≥50 °C. In contrast, the ambient temperatures experienced by other crewmembers on the same fire did not exceed 39 °C. The individual's total fluid intake was 5.9 liter and was consumed at an average rate of 840 mL/h over the 7 h preceding the HRI. This level of fluid intake was higher than fellow crewmates and was achieved by 24 ± 11 drinks episodes/h which was also more frequent than fellow crewmembers (9 ± 6 drinks/h). Despite this aggressive fluid intake behavior, heat exhaustion occurred, and $T_c$ peaked at 40.1 °C. Meanwhile, the $T_c$ of the other crew members did not exceed 38.5 °C and they did not develop heat illness. There was an ample gradient between $T_c$ and $T_{sk}$ in the 2 h preceding the HRI ($\Delta 4.8 \pm 3.8$ °C), indicating that there was a large potential for heat dissipation. Moreover, the individual's aggressive drinking had prevented excessive dehydration. The individual's excessive rise in $T_c$, therefore, was largely due to working at an exercise intensity that produced too much metabolic heat for the ambient conditions, and consequently, $T_c$ rose to excessive levels. The individual was evacuated from the fireline by helicopter, was treated at the local hospital, and released the same day.

The adequacy of the fluid intake data in the above-mentioned studies (33, 132) reveals that dehydration was not a major contributor to the magnitude of hyperthermia or the risk for heat injury. Instead, these data and the cumulative body of work in this area indicate that heat intolerance during wildland fire assignments aligns most closely with the mismanagement of work:rest intervals, leading to heat storage and an inability to adequately offload the metabolic heat production (37, 132). Therefore, safety messages and fireline tactics should focus attention on managing the heat load, either by reducing work rate or including more frequent rest breaks away from ambient heat sources as the primary strategy to reduce heat illness risk. Focus on aggressive fluid intake at the expense of attention to behaviors that will either lower heat production or aid in heat dissipation may instill a false sense of protection during arduous wildfire management. Simply stated, aggressive fluid intake strategies do not adequately compensate for metabolic heat production, high ambient temperatures, and/or inadequate preseason aerobic conditioning which can culminate in uncompensated heat stress.

## Altitude

The ability to work effectively and safely at moderate and higher terrestrial altitudes is a separate environmental challenge for the WLFF. Analyses from continuous GPS data indicate that WLFFs operating in the western US performed their fire assignments at an average working altitude of 1505 ± 707 m with a recorded max of 3326 m (119). Although these altitudes are unlikely to compromise expected work rates or induce acute mountain sickness, higher altitude assignments present an additional physiological strain and could contribute to deterioration in performance capability when combined with the other environmental stressors. The altitude-induced limitations to work shift performance could become manifest from decreases in aerobic capacity (54) and the cumulative effects of lower oxygen saturation which heighten the risk of acute mountain sickness (94),



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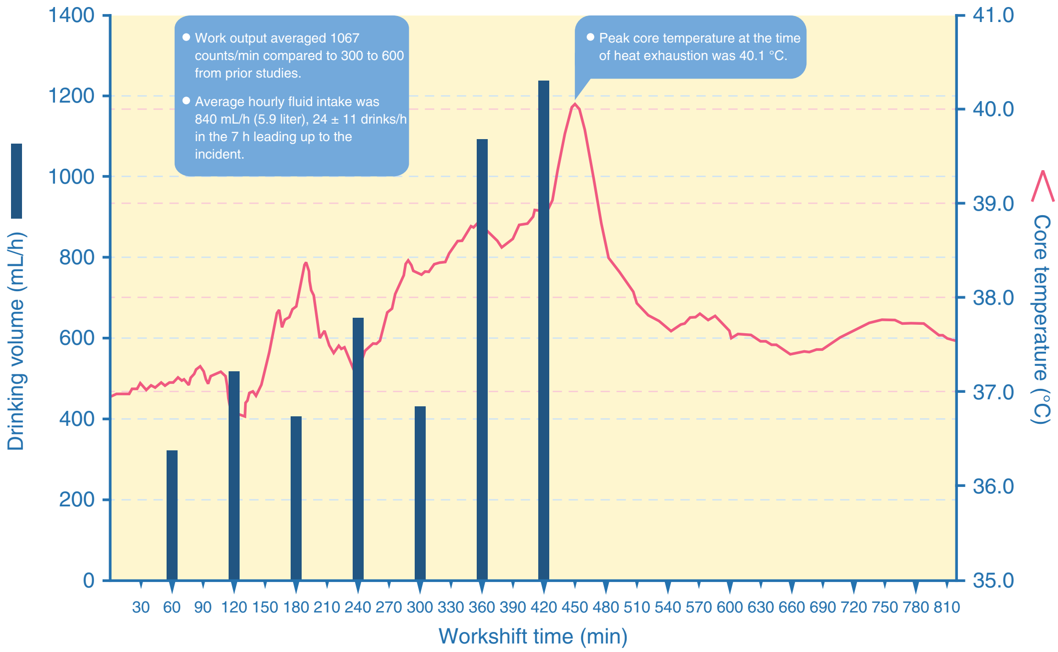


Figure 3 Timeline of a heat-related injury during arduous wildland fire management with the individual drinking behavior prior to presenting with heat injury and their body core temperature over time. Adapted, with permission, from Cuddy JS and Ruby BC, 2011 (37).

alter reaction time (52), diminish decision-making capacity, and lower the overall health and safety of wildland fire crews.

## Smoke exposure

Smoke exposure is an occupational hazard for WLFFs. The number of pathogenic pollutants is highest with prescribed burns that utilize petroleum-based fuels, and lowest when combating the early stages of a wildland fire (2, 99). Carbon monoxide, formaldehyde, nitrogen oxides, polycyclic aromatic hydrocarbons, volatile organic compounds, and secondary particulate matter (PM) comprise many of the pollutants produced in wildfire smoke and can compromise human health (81). Fine PM ($PM_{2.5}$), a component of wood smoke, heightens risk of respiratory morbidity, and all-cause mortality (20). The American Heart Association has also identified $PM_{2.5}$ inhalation as a contributory risk factor for cardiovascular morbidity and mortality (11), including the precipitation of acute cardiac events (84). The underlying mechanism(s) for these various pathological outcomes are likely connected to the accumulation of $PM_{2.5}$ within the lungs where it can then induce chronic inflammation and oxidative stress. Sustained levels of PM-induced inflammation are ultimately responsible for multiple pathological sequalae throughout the cardiovascular system (93). In fact, increased risks for atherosclerosis, plaque destabilization, peripheral thrombosis, hypertension, dysrhythmia, and/or myocardial ischemia have all been linked to $PM_{2.5}$ exposure (93). Recently completed studies in mice now suggest that $PM_{2.5}$ exposure directly promotes chronic inflammation, oxidative stress, and increased lipid droplet size in liver tissue; simultaneously initiating dyslipidemia and nonalcoholic liver disease (141). Clinical studies designed to mimic conditions of $PM_{2.5}$ exposure and physical work in WLFFs (3) further confirm deleterious alterations in markers of inflammation and oxidative stress within 90 min of $PM_{2.5}$ exposure. Elevated biomarkers following $PM_{2.5}$ exposure were observed simultaneously in multiple tissues, as indicated by increased pentraxin-3 (PTX3) and 8-isoprostane levels in plasma and exhaled breath condensate (EBC) (44, 90). Therefore, indications from clinical laboratory-based studies seem to corroborate a causative link between $PM_{2.5}$ exposure and dyslipidemia, which in turn can lead to hepatic steatosis.

The dispersion of the wood smoke affects the inhaled dose and is likely to impact the physiological response to pollutants (22). For example, studies conducted in young school children exposed to wood smoke-polluted air did not present alterations in hydrogen peroxide or EBC pH (43). On the other hand, urinary 1-hydroxyprene was elevated, indicating relatively modest exposure to polycyclic aromatic hydrocarbons (62). Even though inherent variations to smoke exposure were reduced by recruiting children from the same metropolitan private school (and validated by the recording of symptom diaries), daily $PM_{2.5}$ levels commonly fluctuated by at least twofold within a given location (125). Calm winds were associated with $PM_{2.5}$ levels and reached levels tenfold higher (i.e., 165 mg/m$^3$) than particulate counts when there were modest wind conditions. The combustive and



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unpredictable nature of wildland fires is often associated with strong winds (6) and greater dispersion of the wood smoke. Accordingly, quantification of $PM_{2.5}$ levels is now routinely tracked at each fire. The combination of remote particulate sensing and global positioning system-based asset tracking is being used to improve the safety of WLFFs engaged in wildfire management (8). Yet, long-term and high-dose $PM_{2.5}$ exposures remain an occupational hazard with the potential to impact metabolic health.

The physical nature of a WLFFs work enhances their air pollutant exposures. The heightened ventilation depth and rates during physical labor increase the volume of air entering the lungs and the accumulation of particulates in the respiratory system (86). While it remains difficult to quantify directly in human studies, the accumulation of PM in the lungs is believed to further exacerbate systemic oxidative stress and inflammation responses to physical activity performed in a smoky environment (63, 89).

Obvious concerns then arise for WLFFs as physical exertion and high TDEE are fundamental elements of the job (40, 109). One potential countermeasure is to improve the preseason cardiorespiratory fitness of the individual WLFF, thereby lowering the ventilatory rate for a given sub-maximal level of physical exertion. Accordingly, any individual seeking work as a WLFF is encouraged to begin physical conditioning at least 4 weeks before the start of the season (116). As described previously, heterogeneity in preseason values of sustainable aerobic capacity ($T_{vent}$) and maximal oxygen consumption ($\dot{V}O_{2\ peak}$) (47) is common within a given crew. Over the course of the season, however, $T_{vent}$ values merged to a more homogenous average with less individual variability around that mean; reflecting a decay in the fittest individuals, and positive changes in crew members who started the season less fit (as previously discussed).

These observations not only suggest that operational fitness presents in a more homogeneous fashion throughout the season but that declines in the $T_{vent}$ (and the corresponding ventilatory rate for any submaximal workload) in some preseason fit individuals may contribute to an elevated metabolic risk subsequent to aerobic detraining. In support, preliminary evidence, from laboratory studies of smoke inhalation concentrations and work rates that mimic WLFF scenarios, indicates systemic oxidative stress and chronic inflammation occur due to elevated ventilatory rates during treadmill walking (44, 90). Additional studies are needed to delineate linkages between seasonal changes in cardiorespiratory fitness, metabolic risk, and stress biomarkers related to smoke exposure.

## Psychological stress

Elevated levels of depressive symptoms and posttraumatic stress disorder (PTSD) have been reported in WLFFs after extended fire seasons (7, 68, 95). The prevalence of PTSD within these WLFFs varied from approximately 12% to 25%. By comparison, the incidence of PTSD in Special Operations Forces personnel has been reported to range from approximately 16% to 20% (57). Incidentally, the causes of the reported stresses are not well defined in WLFFs but may be a function of the inherent nature of seasonal work or the operational schedule. However, several factors likely contribute to this growing area of concern.

Emotional changes are troubling when viewed in the context that coming fire seasons are expected to be longer and the fires more frequent and larger in scale in the foreseeable future. As these changes in fire manifest, it may mean WLFFs will spend additional time away from their family and away from home, while experiencing accumulating physical and emotional fatigue. None of which suggests that the emotional challenges will be lessened. As such, countermeasures are needed.

The psychological literature indicates that social support and beneficial community integration mechanisms can lessen psychological symptoms. Left untreated these symptoms can worsen and even persist for decades after the original work-related trauma (80, 88) and contribute to the development of metabolic syndrome (131). PTSD perturbs the hypothalamic-pituitary-adrenal axis. Dysregulation of this hormonal axis promotes elevations in circulating cortisol; ultimately increasing the risk of type 2 diabetes, dyslipidemia, insulin resistance, and chronic inflammation (105). Fortunately, recent studies report that emotional support from family, friends, and coworkers offer protective benefits against undue stress in the operational environment (60).

## Disrupted sleep

Sleep is a separate emergent topic within the firefighting community; both the untoward effects lack of restorative sleep can have on performance and decision-making, but also its contribution to emotional resiliency. The extended travel to fires, rudimentary sleeping conditions, and consequent exposure to extreme environments, can each hinder the volume and quality of sleep in this community. Epidemiological studies indicate that poor sleep hygiene, in physically and mentally stressful environments is associated with multiple health outcomes. For example, work-related declines in self-reported sleep quality within 2941 military service persons, were associated with corresponding declines in mental health (PTSD, trauma processing, etc.) (122).

The impact of sleep disruption has been studied within the WLFF community (14, 21, 127–129). Observational studies suggest that sleep behavior varies considerably across crews, regions, and even individual fire events. Studies have also examined the impact of acute sleep restriction on performance indicators. For example, a study randomized WLFF participants to normal sleep (8 h) and sleep-restricted (4 h) groups during live wildfire assignments. The authors reported that metrics of fatigue increased in the sleep-restricted group, and firefighting performance tasks (e.g., raking, hose rolling, etc.) were nominally—but not statistically—lower. One caveat limiting this conclusion, however, is that the fire was of relatively low intensity and did not put undue physical



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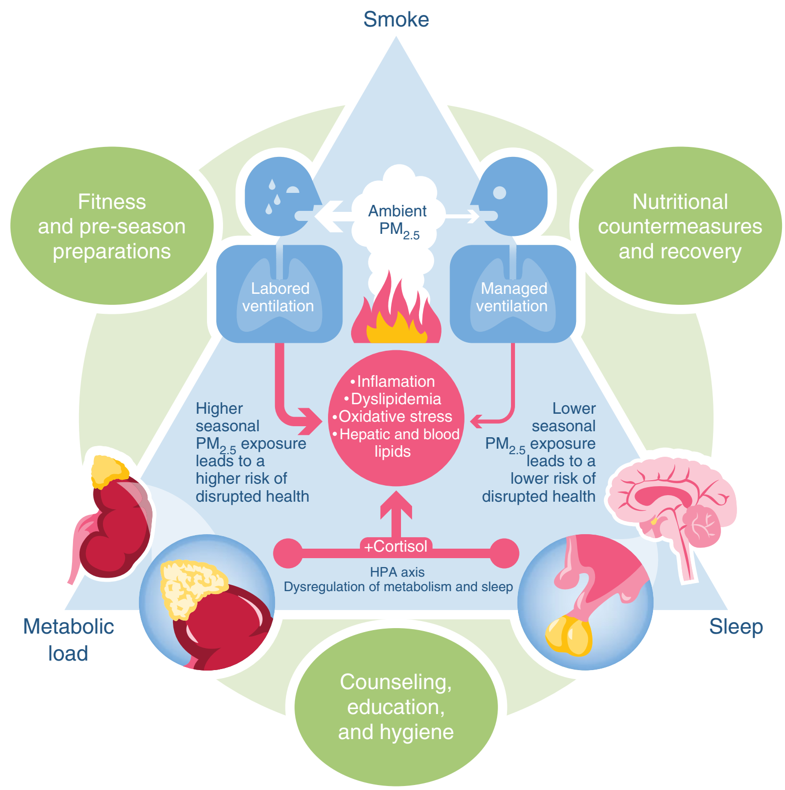


Figure 4 Theoretical concepts surrounding the occupational factors of wildland fire management that influence deconditioning, pollutant exposure, and chronic stress triad (DPST) and potential countermeasures that may reduce seasonal health in wildland firefighters. $PM_{2.5}$, fine particulate matter.

stress on the participants (127). Accordingly, it appears that the application of findings from sleep research in WLFFs is contingent upon the relationship between the sleep metrics and the magnitude of stress experienced within the immediate work environment (75). In support, in a more recent publication actigraphy was used to quantify sleep duration during low-intensity and high-intensity wildland fire fighting scenarios. In their investigation, McGillis et al. documented a significant drop in total sleep time (TST) during strenuous initial attack fire deployments (an average of 1 h, 25 min less sleep). Moreover, while shift length (e.g., <12 h, 12–13 h, >13 h) and the time of day associated with the end of the work shift (e.g., <7 PM, 7–8 PM, 8–9 PM, >9 PM) had nonstatistical impacts on sleep quantity, beginning shifts between 5 and 6 AM had the most significant influence on sleep duration (~1 h less sleep on average) (75). The results of these studies have obvious safety implications during wildfire management, and the downstream consequences of poor sleep may negatively affect stress resilience and contribute to an increased risk for metabolic derangement.

## Comprehensive health concerns

Cumulative evidence strongly suggests that WLFF experience a myriad of factors which may increase the overall risk for cardiometabolic abnormalities (44, 138, 139). Evidence from preclinical studies directly link smoke exposure (cigarette) to cholesterol transport and dyslipidemia (142). As it stands, we know that particulate exposure, marginal fitness, and cumulative stress influence metabolism and resilience (23, 82). Unknown, however, is whether these factors synergistically affect cardiometabolic health in an unscripted field setting involving extended wildland fire management and the comprehensive stresses involved.

Figure 4 provides an overarching theoretical model of what factors could be contributing to the apparent untoward cardiometabolic shifts being observed in WLFFs. Also, the paradigm considers the singular and combined influences that particulate exposure, inadequate preseason conditioning versus deconditioning, chronic stress, and inadequate sleep could play in the shifts observed and can serve as a guide for additional research and countermeasure development. We propose a deconditioning, pollutant exposure, and chronic stress triad (DPST) oriented model for future research considerations. This comprehensive approach attempts to outline the combined stressors that may work synergistically to impair healthy seasonal outcomes. While some countermeasures have been tested in past research with crews and others (33, 35, 47, 71), more work is needed as none of these approaches have attempted to address smoke inoculation,



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stress, or sleep loss. Educational materials that clearly outline available resources (nutrition, preseason training, recovery, counseling support tools, and incident-oriented sleep hygiene) are also warranted to reduce the risk factor triad summarized in Figure 4.

## Pulling It All Together

Unique and valuable insight into the work life of WLFFs, and the physiological burdens experienced by this specialized workforce (both daily and over the course of a fire season), have been gleaned using a variety of experimental methods and approaches. WLFF demographic profiles have been characterized, and the overall energy and water budgets of crewmembers on assignment are now known. Historic and recent data have led to an understanding of the acute metabolic demands of various fireline tasks including hiking with a load and working with hand tools for fireline construction and maintenance. Additional work has detailed the expected heat and cardiovascular strain responses to unique ambient and metabolic heat production; issues that are managed effectively by WLFFs through strategic work:rest cycles and adequate fluid intake. Dietary intake and evaluation studies have delineated fatigue countermeasure strategies while also demonstrating that the need for nutritional supplements is likely unwarranted when adequate TEI is met with *ad libitum* eating. Moreover, these comprehensive physiological responses have been evaluated in both female and male WLFFs over multiple decades of data collection. These comprehensive findings are detailed in Figure 5.

## Conclusion

WLFFs play critical roles in the management of wildfire outbreaks. Their work requires long hours of physical labor in arduous environments that pose injury and health risks.

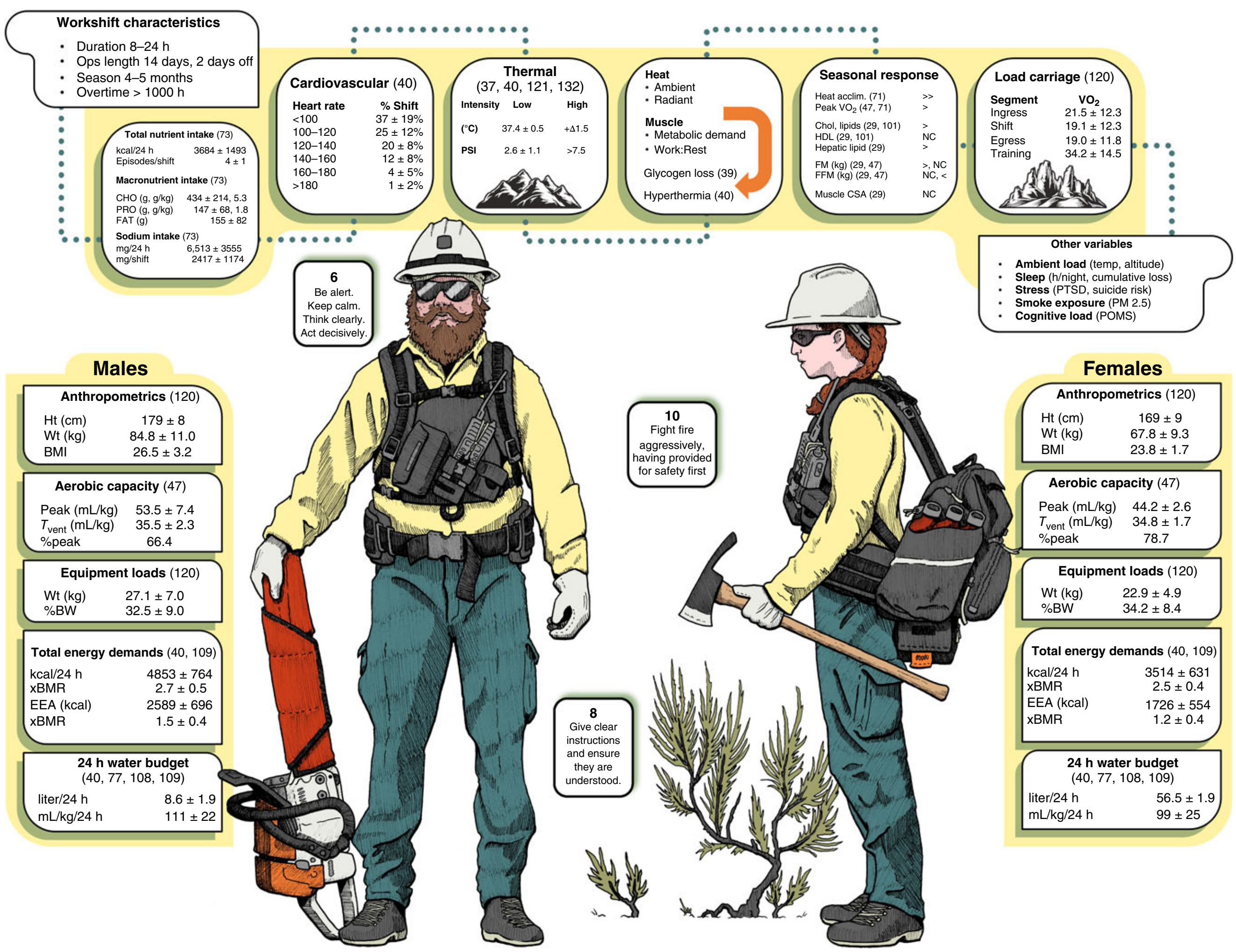


Figure 5 Physical characteristics of male and wildland firefighters on assignment and a comprehensive description of the measured energy demands, fluid budgets, nutrient intake, work shift characteristics (length, equipment, cardiovascular, and thermal loads), and seasonal responses and their relationship to the Standard Fire Orders (4).



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WLFFs face numerous challenges, as they must refeed at rates that are sufficient to sustain their high daily energy expenditures and drink sufficient fluid volumes to match their high, water turnover. Sleep can be difficult both when traveling to their fire assignment and in the remote areas where they operate. WLFFs are chronically exposed to complex pollutants in fire smoke. In this article, we have characterized the physical demands of their occupation, the typical demographics and fitness characteristics they possess, and the physical and emotional toll of seasonal work. Figures 4 and 5 synthesize what we know about the physiology of the wildfire workforce and possible contributors to emergent health risk factors we have documented in WLFFs across the fire season (29, 101).

## Call to Action

As the incidence and intensity of the fire season and wildfires are expected to increase, it can be anticipated that WLFFs will face a larger physical and emotional burden. Characterization of their drinking and nutritional behaviors, thermal strain and environmental exposures, and dynamic health status changes are now informing logistics and safety personnel who work to meet WLFF needs and to protect their safety. In addition, the accumulating body of published data is informing the development of countermeasures to protect WLFF performance and health. The recent observations that blood lipid and other health status markers are being negatively affected over the fire season is driving research to better understand the causative agents and whether countermeasures are needed to protect the near- and long-term health of WLFFs. It is our hope that this article will fuel further investigation to best protect WLFF health and their well-being, and the development of crew-oriented comprehensive and targeted education materials. It is advised that when emerging evidence indicates a change in policy or best practice is warranted, that administrators, clinicians, health care providers, and fire crew members collectively participate in the crafting of the new policy or practice.

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